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Systematic Review

Adhesion and Interfacial Durability of Coatings on NiTi Alloys Under Tribocorrosion Conditions: A Review

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Abstract

The performance and long-term reliability of nickel–titanium (NiTi) alloys in biomedical applications are strongly governed by surface-related degradation processes, in which the adhesion and interfacial stability of protective coatings play a critical role. This systematic review was conducted and reported in accordance with PRISMA 2020. Scopus, Web of Science, and Google Scholar were searched for English-language peer-reviewed literature published from 1995 to 2025. Of 186 records identified, 87 publications were included in the qualitative synthesis. The review examines ceramic, polymer, and hybrid coatings applied to NiTi substrates, with particular emphasis on adhesion mechanisms, interfacial mechanics, and tribocorrosion behavior under coupled mechanical and electrochemical loading conditions. The analysis demonstrates that coating durability is controlled by the interplay between adhesion characteristics, mechanical compatibility, and functional thickness. Thin coatings provide favorable strain accommodation but limited wear resistance, whereas thicker layers improve barrier performance at the expense of increased susceptibility to interfacial stress accumulation and cracking. Ceramic coatings offer excellent corrosion and tribological performance but are prone to adhesion-related failure under large deformation, while polymer coatings enhance interfacial compliance at the cost of reduced long-term durability. Multilayer and graded architectures improve adhesion durability and delay delamination by redistributing interfacial stresses and decoupling protective and deformational functions. Despite significant progress, key challenges remain, including limited long-term fatigue data, insufficient tribocorrosion studies under fully coupled conditions, and the lack of predictive models linking interfacial design with coating durability.

Keywords: NiTi alloys; nitinol; tribocorrosion; surface coatings; interfacial mechanics; martensitic transformation; biomedical materials

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1. Introduction

Nickel–titanium alloys (NiTi, commonly referred to as Nitinol) represent one of the most important classes of functional biomaterials used in modern biomedical engineering. Their unique mechanical behavior arises from a reversible martensitic phase transformation between austenite and martensite, which enables large recoverable strains (up to several percent under favorable loading conditions) while maintaining relatively high mechanical strength and fatigue resistance [1–4]. Owing to these properties, NiTi alloys have been widely implemented in biomedical devices requiring high flexibility and mechanical reliability, including vascular stents, orthodontic components, and various orthopedic implants [3–7].

Despite their exceptional functional properties, the long-term performance of NiTi components in physiological environments is governed predominantly by surface-controlled degradation phenomena. The alloy is naturally protected by a passive TiO_2 layer that provides a certain degree of corrosion resistance; however, the stability of this protective film may be compromised under mechanical loading or in aggressive environments containing chloride ions [8–11]. Disruption of the passive layer can lead to increased electrochemical activity, accelerated corrosion processes, and enhanced nickel ion release, which may influence both the durability of the implant and the biological response of surrounding tissues [9,12].

A particularly important degradation mechanism affecting NiTi biomedical devices is tribocorrosion, which results from the simultaneous interaction between mechanical wear and electrochemical corrosion. Unlike purely mechanical or purely electrochemical degradation processes, tribocorrosion involves complex synergistic interactions that often accelerate material loss and destabilize protective surface films [8,13,14]. Experimental studies have demonstrated that mechanical removal of the passive oxide layer leads to a local increase in corrosion current density and promotes progressive surface degradation during repeated contact or sliding conditions [13,15,16].

To mitigate these limitations, extensive research has focused on advanced surface modification strategies designed to enhance the durability and biological performance of NiTi alloys [17–20]. Among the most widely investigated approaches are ceramic coatings, polymer coatings, and hybrid multilayer systems [17–19,21]. Ceramic coatings such as titanium dioxide (TiO_2) and diamond-like carbon (DLC) can significantly improve wear resistance and electrochemical stability, whereas polymer coatings offer superior mechanical compliance with the deformable NiTi substrate and may enhance biocompatibility [17–19]. In addition, increasing attention has been devoted to multifunctional coating concepts capable of providing antibacterial activity, improved biointegration, or controlled release of therapeutic agents [22–31].

From the perspective of adhesive science, the performance of such coatings is governed not only by their intrinsic protective properties but, critically, by the nature and durability of the coating–substrate interface. Adhesion in NiTi-based systems should therefore be considered as an interfacial property controlled by a combination of chemical bonding, mechanical interlocking, and interfacial fracture resistance, rather than solely by initial adhesion strength values measured under simplified loading conditions [20].

Designing durable coating systems for NiTi alloys consequently requires careful consideration of the complex coupling between mechanical deformation, electrochemical processes, and interfacial mechanics. In particular, mechanical compatibility between the coating and the superelastic substrate is critical. Significant differences in elastic modulus may generate strain incompatibility at the coating–substrate interface, leading to stress concentration, microcrack initiation, and progressive interfacial damage during cyclic loading [32,33]. For this reason, multilayer and compositionally graded coating architectures are increasingly investigated as strategies for redistributing stresses and improving interfacial stability under repeated deformation [20,28,34,35].

The present article provides a critical review of surface engineering strategies applied to NiTi alloys, with emphasis on ceramic, polymer, and hybrid coating systems. Particular attention is devoted to adhesion mechanisms, interfacial fracture and stress development, the influence of coating thickness and architecture, and the multiphysical degradation processes associated with tribocorrosion. By integrating insights from materials science, tribology, electrochemistry, and adhesive mechanics, this review aims to clarify the relationships between coating design, interfacial durability, and the long-term functional performance of NiTi biomedical devices.

2. Methodology of the Systematic Review

2.1. Review Design and Reporting Standard

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) statement [36]. The completed PRISMA 2020 Checklist is provided as Supplementary File S1.

Systematic Review Registration

The review protocol was not prospectively registered in PROSPERO or any other public registry, and no publicly accessible protocol was prepared.

2.2. Eligibility Criteria

Publications were eligible when they: (i) addressed NiTi or Nitinol substrates; (ii) investigated a coating, surface layer, or surface-modification strategy relevant to adhesion, interfacial durability, corrosion, wear, tribocorrosion, or biomedical functionality; (iii) were published in English between 1995 and 2025; and (iv) were peer-reviewed journal articles or authoritative review papers. Conference abstracts, patents, technical reports, non-peer-reviewed publications, non-English publications, and studies not directly related to coated or surface-modified NiTi were excluded. Review papers were used to support contextual synthesis, whereas quantitative values in the comparative tables were extracted from the corresponding primary studies whenever available.

2.3. Information Sources and Search Strategy

Scopus, Web of Science, and Google Scholar were searched. The search combined terms describing the substrate, coating strategy, and degradation or adhesion outcome. The core Boolean structure was: ("NiTi" OR "Nitinol" OR "nickel titanium") AND (coating * OR "surface modification" OR "surface treatment") AND (adhesion OR interface * OR tribocorrosion OR corrosion OR wear OR ceramic OR polymer OR hybrid OR "diamond-like carbon" OR hydroxyapatite). Additional targeted combinations were used to identify studies on TiO_2, DLC, HAp, ALD, EPD, residual stress, roughness, and martensitic transformation. Reference lists of relevant review papers and included articles were also checked for additional eligible publications.

The final search update was performed on 7 July 2026.

2.4. Selection Process

After deduplication, titles and abstracts were screened against the eligibility criteria. Potentially relevant records were then assessed in full text. Publications were excluded at the full-text stage when they did not concern NiTi, did not address coatings or surface-modification effects relevant to the review questions, or did not provide sufficient information for qualitative synthesis. The screening decisions and any uncertainties were resolved through discussion between the authors.

2.5. Data Collection and Data Items

For each eligible publication, the authors extracted, where reported, the coating material and architecture, NiTi substrate preparation, deposition method and processing parameters, coating thickness, surface roughness and morphology, phase and chemical composition, porosity or defects, adhesion-test method and quantitative adhesion results, residual stress, hardness and elastic properties, electrochemical test conditions and parameters, tribological or tribocorrosion conditions, failure mode, and principal functional conclusions. Data were checked against the original publications before inclusion in the comparative tables.

2.6. Assessment of Study Quality and Reporting Completeness

Because the included publications comprised heterogeneous experimental designs, coating systems, test methods, and outcome measures, a single validated risk-of-bias tool applicable to all studies was not available. A formal pooled risk-of-bias score was therefore not calculated. Instead, the review assessed reporting completeness and comparability by checking whether studies provided the substrate preparation, deposition conditions, coating thickness, test environment, loading protocol, quantitative outcome measures, and failure criteria required for interpretation. Missing parameters are reported as not reported (NR) and are treated as limitations rather than replaced with estimated values.

2.7. Synthesis Methods

The included literature was synthesized qualitatively and comparatively. Studies were grouped by coating class and by the principal mechanisms relevant to surface degradation, adhesion, interfacial mechanics, strain compatibility, and tribocorrosion. Numerical values were tabulated only when they were explicitly reported in the source publication. A meta-analysis was not performed because of substantial heterogeneity in coating composition, substrate geometry and preparation, deposition parameters, loading schemes, electrochemical environments, and outcome definitions.

2.8. Study Selection

A total of 186 records were identified. After removal of 41 duplicates, 145 records were screened by title and abstract. Thirty-four records were excluded at this stage, and 111 full-text reports were assessed for eligibility. Twenty-four full-text reports were excluded for the reasons shown in Figure 1. Ultimately, 87 publications were included in the qualitative synthesis and comparative analysis.

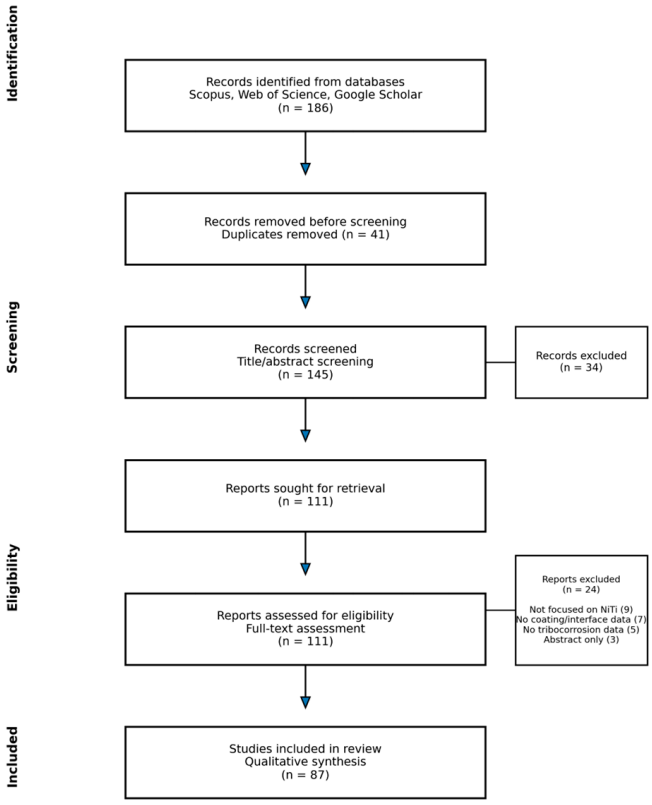


Figure 1. PRISMA 2020 flow diagram of study selection. Prepared by the authors in accordance with the PRISMA 2020 statement; not reproduced from a previously published source.

2.9. Limitations of the Review

Several limitations of this review should be acknowledged. The analysis was restricted to publications indexed in Scopus, Web of Science, and Google Scholar and published in English between 1995 and 2025. Conference abstracts, patents, technical reports, and non-peer-reviewed sources were excluded. Furthermore, the available literature frequently lacks complete reporting of parameters relevant to interfacial mechanics, including residual stress, elastic modulus, coefficient of thermal expansion, porosity, and long-term tribocorrosion performance. Consequently, quantitative comparisons between coating systems are sometimes limited by inconsistencies in experimental methodologies and reporting practices across studies.

3. Surface Degradation Mechanisms

The long-term performance of NiTi alloys in biomedical environments is governed primarily by surface-controlled degradation phenomena. Although NiTi exhibits excellent corrosion resistance compared with many conventional metallic biomaterials, its durability depends on the stability of the passive oxide layer and its ability to withstand simultaneous mechanical and electrochemical loading. Surface degradation of NiTi is therefore a multiphysical process involving passive film breakdown, corrosion, tribological wear, tribocorrosion, nickel ion release, and mechanically induced damage associated with cyclic martensitic transformation [10,37].

3.1. Structure and Protective Function of the Passive TiO_2 Layer

The corrosion resistance of NiTi originates from the spontaneous formation of a titanium-rich passive oxide layer on the alloy surface [38,39]. Under physiological conditions, the passive film consists predominantly of TiO_2 with minor contributions from suboxides such as Ti_2O_3 and TiO. The outermost region is generally enriched in titanium oxides, whereas nickel concentration is significantly reduced relative to the bulk alloy. This compositional gradient is critical because it limits direct exposure of nickel-containing phases to the surrounding biological environment [38].

For mechanically polished NiTi surfaces exposed to physiological solutions, the naturally formed passive layer is typically only a few nanometers thick, commonly in the range of approximately 1–4 nm. Surface engineering treatments can substantially increase this thickness. Low-temperature plasma oxidation has been shown to generate nanocrystalline rutile-rich TiO_2 layers approximately 29–55 nm thick, while ALD-derived coatings frequently produce continuous oxide films of approximately 50 nm thickness [37,38,40].

The protective efficiency of the passive layer depends not only on thickness but also on crystallinity, porosity, defect density, and residual stress. Dense, low-defect rutile-rich layers generally exhibit higher corrosion resistance and lower nickel release than porous or mechanically damaged films. Conversely, pores, microcracks, and compositional discontinuities may serve as preferential sites for localized electrochemical activation [37,41].

3.2. Passive Film Breakdown and Localized Corrosion

Although the passive film possesses self-healing capability, its stability is challenged in chloride-containing physiological environments [39]. Chloride ions penetrate defects in the oxide layer and promote local dissolution processes. When the protective barrier is disrupted, electrochemical activity increases and localized corrosion processes may initiate [31,39].

The anodic reaction occurring at damaged regions can be simplified as:

$$Ti \rightarrow Ti^{4+} + 4e^{-}$$

while cathodic reactions are dominated by oxygen reduction:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

or, under oxygen-deficient conditions:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

The competition between metal dissolution and repassivation determines the long-term stability of the surface. If repassivation proceeds rapidly, the oxide layer reforms and corrosion remains limited. However, repeated mechanical damage may prevent complete restoration of the protective barrier and promote progressive degradation [42].

Electrochemical studies of NiTi commonly report corrosion current densities in the sub-microampere range and relatively broad passive regions, indicating good corrosion resistance. Nevertheless, passive film disruption can increase current density by several orders of magnitude locally, particularly under tribological loading [10,38].

3.3. Tribocorrosion as a Coupled Degradation Process

Tribocorrosion is widely recognized as one of the most important degradation mechanisms affecting NiTi implants [43–45]. Unlike pure wear or pure corrosion, tribocorrosion results from the simultaneous interaction of mechanical contact and electrochemical reactions, producing a synergistic effect that accelerates material loss [10,37].

During sliding or fretting contact, the passive TiO_2 film is mechanically removed from the surface. The newly exposed substrate becomes electrochemically active and undergoes accelerated dissolution. Repassivation begins immediately; however, if mechanical contact persists, the oxide layer is repeatedly disrupted before complete restoration can occur. The result is a dynamic cycle consisting of:

1. Passive film removal;
2. Electrochemical activation;
3. Metal dissolution;
4. Repassivation;
5. Renewed mechanical damage.

This repetitive sequence produces substantially higher degradation rates than would be predicted from independent wear and corrosion processes [10,42,46].

The total material loss can therefore be expressed as:

$$T = W + C + S$$

where T is total material loss, W is pure wear, C is pure corrosion, and S represents the synergistic wearcorrosion contribution. In passive metallic systems, the synergistic term often constitutes a significant fraction of total degradation [37,42,47].

3.4. Influence of Martensitic Transformation on Surface Degradation

A unique aspect of NiTi degradation is the interaction between tribocorrosion and stress-induced martensitic transformation. During loading, localized transformation between austenite and martensite alters surface stress distributions and contact mechanics. These changes influence crack initiation, passive film stability, and local electrochemical behavior [10].

Repeated transformation cycles may produce cyclic strain accumulation at coating–substrate interfaces and near-surface regions. In coated systems, strain incompatibility between the substrate and the coating can accelerate crack formation and interfacial damage. Consequently, degradation cannot be analyzed solely from the perspective of corrosion resistance; mechanical compatibility must also be considered [10,37].

3.5. Wear Debris and Degradation Products

Mechanical and tribocorrosion processes generate wear debris consisting of oxide fragments, detached coating particles, metallic particles, and corrosion products. The composition of these degradation products depends strongly on coating architecture and environmental conditions.

For uncoated NiTi, debris frequently contains titanium oxides and nickel-containing species formed during repeated oxidation and mechanical fragmentation. In coated systems, degradation products may additionally contain ceramic particles, hydroxyapatite fragments, carbonaceous debris from DLC coatings, or polymer fragments from compliant coatings [10,48].

The biological significance of wear debris is increasingly recognized because particle generation may influence inflammatory response, local tissue compatibility, and implant longevity. Consequently, future tribocorrosion studies should combine electrochemical measurements with detailed physicochemical characterization of degradation products [10,37].

3.6. Implications for Coating Design

The degradation mechanisms discussed above demonstrate that the durability of coated NiTi systems is governed by the stability of the passive film, resistance to mechanical damage, efficiency of repassivation, and compatibility between coating and substrate deformation. Surface engineering strategies should therefore aim not only to increase corrosion resistance but also to minimize strain-induced cracking, reduce defect density, and maintain passive film integrity during cyclic loading. Multilayer, graded, and hybrid coating architectures are particularly promising because they simultaneously address electrochemical protection and mechanical compatibility requirements [10,37].

4. Surface Morphology and Microstructural Characterization of Coatings on NiTi

The microstructural state of the NiTi surface and of the applied coating determines adhesion durability, corrosion protection, tribological response, and biological performance. Therefore, the evaluation of coating performance should not be limited to macroscopic parameters such as coating type or nominal thickness, but should include surface morphology, roughness, coating continuity, porosity, phase composition, chemical gradients, and the structure of the coating–substrate interface. These features control the real contact area, mechanical interlocking, local stress concentration, defect-assisted crack initiation, and the stability of the passive oxide layer during mechanical or electrochemical loading [12,16,37,49–55].

4.1. SEM-Based Evaluation of Coating Morphology and Continuity

Scanning electron microscopy (SEM) is the most frequently used method for assessing the morphology and continuity of coatings on NiTi. SEM enables identification of pores, cracks, particle agglomerates, local discontinuities, and coating defects that may act as initiation sites for tribological damage or interfacial delamination. In electrophoretically deposited Ag-TiO_2 nanocoatings, SEM observations showed that deposition voltage and time strongly affect coating homogeneity; low-voltage/short-time conditions may produce unevenly distributed agglomerates, whereas optimized conditions can yield a more continuous and crack-free ceramic layer [50]. Similar morphology-sensitive behavior was reported for HAp/Ag-TiO_2 hybrid coatings, where hydroxyapatite incorporation changed surface development and affected adhesion, wettability, antibacterial response, and corrosion behavior [49,51].

For plasma-oxidized NiTi, SEM analysis demonstrates that oxide-layer morphology depends strongly on surface preparation and oxidation parameters. Mechanically ground and mechanically polished substrates respond differently to low-temperature plasma oxidation, indicating that the initial topography of the NiTi surface is not only a preparatory variable, but a structural factor governing final oxide morphology [37,52]. This is important for coated superelastic systems, because local topographic heterogeneity may promote non-uniform strain transfer from the deformable substrate to the coating during cyclic loading.

4.2. AFM and Profilometry: Roughness as an Adhesion-Relevant Parameter

Atomic force microscopy (AFM) and optical profilometry provide quantitative information on nanoscale and microscale roughness. Roughness can enhance adhesion by increasing the effective contact area and promoting mechanical interlocking; however, excessive roughness may also create stress concentrators and increase local electrochemical heterogeneity. In plasma-oxidized NiTi, profilometry showed that surface preparation before oxidation dominated the resulting topography, while oxidation altered the roughness differently for ground and polished substrates [52]. In thermally treated nitinol wires, AFM revealed that chemical treatment and subsequent oxidation can transform the initial scratched surface into a more developed or porous morphology, which then affects the deposition of hydroxyapatite and polymer-based hybrid layers [55].

The role of roughness is therefore dual. Moderate and controlled roughness can improve coating anchoring, whereas uncontrolled roughness, pores, or agglomerates may reduce coating integrity and accelerate crack initiation. For this reason, future comparative tables should report roughness values such as Ra, Rq, or Sq before and after coating deposition whenever available, rather than describing surface development only qualitatively.

4.3. TEM, EDS and XPS: Interfacial Structure and Chemical Gradients

Transmission electron microscopy (TEM), energy-dispersive spectroscopy (EDS), and X-ray photoelectron spectroscopy (XPS) are essential for understanding the coating–substrate interface. TEM is particularly valuable for measuring oxide-layer thickness, identifying nanocrystalline or amorphous regions, and detecting interfacial discontinuities. Low-temperature plasma oxidation of NiTi produced TiO_2 surface layers approximately 29–55 nm thick with a predominantly nanocrystalline rutile structure, as shown by microstructural characterization including TEM, SEM, and EDS [52]. These results indicate that even very thin oxide layers can differ substantially in crystallinity, thickness, and defect population depending on treatment conditions.

XPS and EDS complement microscopy by providing information on surface chemistry, elemental distribution, and chemical bonding states. These methods are especially important for NiTi because the protective performance of the surface is associated with enrichment in titanium oxide and suppression of nickel exposure at the outermost surface. In HAp-Nb_2O_5 composite deposits on NiTi, SEM, TEM, XPS, and AFM were used together to evaluate the morphology, chemistry, and surface characteristics of the electrodeposited layers, linking microstructural modification with reduced Ni ion release, in vitro behavior, and antibacterial performance [53,56]. Such multimodal characterization is directly relevant to tribocorrosion studies because local chemical heterogeneity and coating defects can become anodic sites after mechanical damage.

4.4. Microstructure–Property Relationships in Ceramic and Hybrid Coatings

Ceramic and hybrid coatings on NiTi commonly exhibit a trade-off between barrier performance and deformation tolerance. Dense TiO_2-based layers improve corrosion protection, but their ability to tolerate superelastic substrate strain depends on thickness, defect

density, crystallinity, and residual stress state. In contrast, porous HAp-based coatings may improve bioactivity and osseointegration but can be mechanically vulnerable under contact loading. Hybrid architectures, such as Ag-TiO_2, HAp/Ag-TiO_2, Ag-SiO_2-TiO_2, or HAp/polymer systems, attempt to combine chemical stability, biological functionality, and adhesion by introducing multifunctional or graded microstructures [49,51,54,55].

Recent studies highlight that coating functionality depends on more than chemical composition. Ag-TiO_2 and hydroxyapatite-doped Ag-TiO_2 nanocoatings on NiTi were characterized in terms of topography, adhesion, wettability, biocompatibility, antibacterial activity, and corrosion behavior, showing that hydroxyapatite-doped layers improved adhesion while Ag-TiO_2 layers showed stronger corrosion resistance [51]. Similarly, Ag-SiO_2-TiO_2 nanocomposite coatings fabricated by electrophoretic deposition were evaluated in terms of scratch resistance, adhesive strength, corrosion resistance, and functional performance, illustrating the need to correlate surface morphology with mechanical and electrochemical testing [54].

4.5. Implications for Adhesion and Tribocorrosion Durability

From the adhesion perspective, microstructural defects such as pores, interfacial voids, brittle agglomerates, cracks, and abrupt compositional transitions reduce the effective fracture resistance of the coating–substrate interface. Under tribocorrosion conditions, these defects are particularly detrimental because mechanical contact can open cracks or remove weakly bonded regions, while electrolyte penetration promotes localized electrochemical activation. Therefore, coating durability on NiTi should be analyzed as a microstructure-controlled process involving the combined effects of topography, phase constitution, coating continuity, interfacial chemistry, and residual stress [8–11,16,37,49–55].

A systematic review of NiTi coatings should consequently extract and compare not only functional outcomes, but also microstructural descriptors. These include substrate preparation, initial roughness, deposition method, coating thickness, porosity or defect description, phase composition, chemical composition, adhesion test method, critical load or adhesion strength, electrochemical parameters, and tribological conditions. The key microstructural descriptors recommended for inclusion in comparative tables are summarized in Table 1.

Table 1. Microstructural descriptors recommended for quantitative comparison of coatings on NiTi alloys.

Descriptor	Recommended Quantitative Parameter	Typical Method	Relevance to Adhesion/Durability	Representative Sources
Initial substrate topography	Ra, Rq, Sq, polishing/grinding condition	AFM, optical profilometry, SEM	Controls real contact area, mechanical interlocking, and local stress concentration	[50,52,55]
Coating thickness and continuity	Thickness in nm or micrometers; continuity/defect description	Cross-sectional SEM, TEM, profilometry	Determines barrier performance, strain tolerance, and stored elastic energy	[37,52,54]
Porosity and surface defects	Pore size, pore density, crack/agglomerate description	SEM, image analysis	Defines crack-initiation sites and electrolyte access paths	[49,50,53]
Phase composition	TiO_2 polymorph, HAp, amorphous/crystalline fraction	XRD, Raman spectroscopy, TEM/SAED	Influences hardness, brittleness, chemical stability, and bioactivity	[49,50,52]

Table 1. *Cont.*

Descriptor	Recommended Quantitative Parameter	Typical Method	Relevance to Adhesion/Durability	Representative Sources
Surface chemistry	Ti/Ni/O/Ca/P/Ag/Nb content; bonding states	EDS, XPS	Controls passivation, Ni exposure, bioactivity, and localized corrosion susceptibility	[51,53,54]
Interfacial integrity	Interlayer presence, voids, cracks, chemical gradient	Cross-sectional SEM, TEM, EDS line scan	Controls delamination resistance and strain transfer	[49,52–54]
Adhesion response	Critical load Lc, pull-off strength, scratch failure mode	Scratch test, pull-off, indentation	Links microstructure with mechanical stability under contact loading	[49,51,54]

5. Adhesion Mechanisms and Interfacial Bonding

The durability of coatings deposited on NiTi alloys depends not only on their intrinsic corrosion resistance or tribological performance, but also on the quality and stability of the coating–substrate interface. In biomedical environments, interfacial degradation may be accelerated by cyclic deformation, local contact, passive-film disruption and electrolyte penetration. Coating failure on NiTi therefore has to be interpreted as a coupled interfacial problem rather than as a simple consequence of insufficient initial adhesion strength [22,23,49,51,54,57].

5.1. Mechanisms Governing Interfacial Adhesion

Adhesion in NiTi coating systems is governed by the combined contribution of mechanical interlocking, oxide-mediated physicochemical bonding, interfacial continuity and residual-stress distribution. Mechanical interlocking is associated with surface topography and roughness; however, the beneficial effect of roughness is limited when surface asperities, pores or particle agglomerates become local stress concentrators. This is particularly important for superelastic NiTi, because large reversible substrate strains can be transferred to brittle or semi-brittle coating layers [12,16,49–52].

The native TiO_2-rich passive layer plays a central role in chemical bonding. For ceramic and hybrid coatings such as TiO_2-, HAp- and Ag/TiO_2-containing systems, the oxide surface provides chemically active sites and enables stronger interfacial interaction than would be expected from purely mechanical anchoring. At the same time, the continuity, crystallinity and defect density of this oxide layer determine whether the interface remains protective during corrosion or becomes susceptible to local electrochemical activation after mechanical damage [12,13,49,51,54].

5.2. Influence of Surface Preparation and Topography

Surface preparation controls both mechanical anchoring and oxide-layer chemistry. Polishing, grinding, chemical treatment, plasma oxidation and electrophoretic pretreatments can generate markedly different surface morphologies and therefore different coating nucleation conditions. Low-temperature plasma oxidation studies show that mechanically ground and mechanically polished NiTi substrates respond differently to oxidation, producing TiO_2 layers with different topographies and microstructures [37,52].

For EPD-derived coatings, the final adhesion response is also sensitive to coating morphology. Ag-TiO_2 coatings deposited on passivated NiTi showed an island-like surface morphology and RMS roughness values of 98 nm, 39 nm and 23 nm depending on scan area,

whereas HAp-Ag-TiO_2 coatings showed lower RMS roughness values of 45 nm, 20.5 nm and 15 nm for the corresponding scan areas [51]. These data indicate that roughness should be reported together with coating architecture and deposition parameters, rather than used as an isolated predictor of adhesion.

5.3. Effect of Deposition Technique and Processing Parameters

The deposition route determines the structure of the coating–substrate interface. ALD produces nanometric, conformal TiO_2 layers with precise thickness control; Rudolf et al. reported TiO_2 thicknesses of 51.7 nm on commercial Nitinol and 52.2 nm on CVC NiTi after 1100 ALD cycles at 250 °C using $TiCl_4/H_2O$ precursors [13]. Although this study focused on electrochemical stability rather than mechanical adhesion testing, the low thickness of ALD layers is relevant for strain compatibility because it limits elastic energy accumulation during substrate deformation.

Electrophoretic deposition enables the formation of bioactive and multifunctional ceramic/hybrid coatings on NiTi, but adhesion depends strongly on voltage, deposition time, suspension composition and heat treatment. Ag-TiO_2 coatings prepared by anaphoresis at 40 V for 3 min and heat-treated at 800 °C for 2 h showed lower critical loads than HAp-Ag-TiO_2 coatings prepared by cataphoresis at 20 V for 1 min and the same heat treatment conditions [51]. Ag-SiO_2-TiO_2 coatings deposited by anaphoresis at 40 V for 3 min and heat-treated at 800 °C in vacuum formed approximately 2.02 ± 0.03 µm thick layers with a continuous SiO_2-TiO_2 interlayer and island-like agglomerates [54].

Polymer coatings provide a different interfacial design strategy. Parylene C (PPX-C) deposited on NiTi by the Gorham CVD process formed 5, 10 and 15 µm thick semi-crystalline layers. The reported delamination forces increased from 231 ± 8 N for 5 µm coatings to 253 ± 8 N for 15 µm coatings, while multiple bending cycles did not produce an adverse adhesion effect in the cited study [57].

5.4. Quantitative Adhesion Assessment

Scratch testing is the most commonly reported method for comparing adhesion and failure progression of ceramic and hybrid coatings on NiTi [58–61]. In progressive-load scratch testing, successive critical loads are assigned to characteristic damage events, commonly denoted as Lc1, Lc2 and Lc3 [62]. These values should not be interpreted as universal adhesion constants because they depend on indenter geometry, loading rate, scratch length, coating thickness, substrate hardness and failure criterion; however, they are useful for comparing coatings tested under identical protocols [49,51,54,63,64].

For Ag-TiO_2 coatings on NiTi, Dudek et al. reported Lc1 = 1.02 ± 0.29 N, Lc2 = 13.42 ± 1.14 N and Lc3 = 20.04 ± 1.31 N. The corresponding failure sequence included gross spallation, arc tensile cracking and complete layer failure [51]. For HAp-Ag-TiO_2 coatings, the same study reported higher critical loads of Lc1 = 2.32 ± 0.27 N, Lc2 = 18.07 ± 2.09 N and Lc3 = 24.41 ± 3.71 N, indicating improved adhesion and greater tolerance to progressive coating damage [51].

For Ag-SiO_2-TiO_2 coatings, Łosiewicz et al. reported Lc1 = 1.56 ± 0.22 N, Lc2 = 4.56 ± 0.08 N and Lc3 = 20.54 ± 1.60 N. These results show that the SiO_2-TiO_2 interlayer and Ag-containing surface architecture changed the damage sequence, although localized pitting remained possible after electrochemical polarization [54]. Quantitative adhesion data extracted from the reviewed studies are summarized in Table 2.

Table 2. Quantitative adhesion, processing and failure data reported for representative coatings on NiTi alloys.

Coating System/Ref.	NiTi Surface/ Preparation	Deposition/ Processing Parameters	Thickness/ Roughness/ Topography	Residual Stress	Adhesion Test/Protocol	Quantitative Adhesion Result	Failure Mode/Remarks
Ag-TiO_2 nanocoating [51]	Passivated NiTi SMA; initial roughness not reported in comparative paper	EPD, anaphoresis; 40 V for 3 min; heat treatment 800 °C for 2 h	Thickness: NR; RMS roughness: 98 nm (10 × 10 µm), 39 nm (3 × 3 µm), 23 nm (750 × 750 nm)	NR	Scratch test; Rockwell diamond 100 µm; 0.03–30 N; 6 mm; 12 mm/min	Lc1 = 1.02 ± 0.29 N; Lc2 = 13.42 ± 1.14 N; Lc3 = 20.04 ± 1.31 N	Gross spallation at Lc1; arc tensile cracks at Lc2; complete layer failure at Lc3
HAp-Ag-TiO_2 hybrid coating [51]	Passivated NiTi SMA; initial roughness not reported in comparative paper	EPD, cataphoresis; 20 V for 1 min; heat treatment 800 °C for 2 h	Thickness: 2 µm; RMS roughness: 45 nm (10 × 10 µm), 20.5 nm (3 × 3 µm), 15 nm (750 × 750 nm)	NR	Scratch test; same protocol as Ag-TiO_2	Lc1 = 2.32 ± 0.27 N; Lc2 = 18.07 ± 2.09 N; Lc3 = 24.41 ± 3.71 N	Plastic deformation at Lc1; discontinuous plastic perforation at Lc2; continuous plastic perforation/complete damage at Lc3
Ag-SiO_2-TiO_2 nanocomposite coating [54]	Passivated NiTi SMA; initial roughness not reported	EPD, anaphoresis; 40 V for 3 min; vacuum heat treatment 800 °C for 2 h	Thickness: 2.02 ± 0.03 µm; continuous SiO_2-TiO_2 interlayer; island-like morphology; Ti 53.5 wt%, O 38.3 wt%, Ni 6.8 wt%, Ag 0.8 wt%, Si 0.6 wt%	NR	Scratch test; same progressive-load protocol	Lc1 = 1.56 ± 0.22 N; Lc2 = 4.56 ± 0.08 N; Lc3 = 20.54 ± 1.60 N	Initial damage followed by cohesive/interfacial spalling; complete failure above 20 N; localized pitting after polarization reported
Parylene C (PPX-C) [57]	Commercial NiTi alloy; ethanol-cleaned surface	Modified CVD/Gorham process; dimer sublimation 160 °C; pyrolysis 650 °C	Thickness: 5, 10, 15 µm; roughness reduced by about 13% for 5 µm and about 20% for 15 µm coatings	NR	Tensile delamination test; repeated bending cycles	Maximum force: 231 ± 8 N (5 µm), 240 ± 5 N (10 µm), 253 ± 8 N (15 µm)	Well-adhered semi-crystalline polymer layer; no adverse adhesion effect after multiple bending cycles reported
ALD TiO_2 [13]	Commercial Nitinol and CVC NiTi rod	ALD in Beneq TFS 200 at 250 °C; $TiCl_4/H_2O$ precursors; 1100 cycles	Thickness: 51.7 nm on commercial Nitinol; 52.2 nm on CVC NiTi; TiO_2 particles 50 nm−1 µm; XPS/SEM-EDX confirmation	NR	Adhesion test not reported	NR	No quantified adhesion failure; study focused on oxide morphology and corrosion resistance

NR = not reported in the cited source. Lc1–Lc3 denote successive critical loads identified during scratch testing. Values are included only where the cited source reports the corresponding quantitative parameter.

5.5. Residual Stresses and Interfacial Failure

Residual stress is a critical but inconsistently reported parameter in the reviewed NiTi coating literature [65–69]. Tensile residual stresses increase the driving force for crack initiation and interfacial delamination, whereas excessive compressive stresses may produce buckling, wrinkling or spallation [68,70–72]. This issue is particularly important for ceramic coatings because of the mismatch between stiff coating layers and the superelastic NiTi substrate [22,23,69,73–75].

A key limitation of the available quantitative studies is that residual stress values and signs are frequently not reported together with adhesion data. For example, the Ag-TiO_2, HAp-Ag-TiO_2, Ag-SiO_2-TiO_2, ALD TiO_2 and PPX-C studies summarized in Table 2 report useful data on thickness, morphology, adhesion or electrochemical response, but they do not provide complete residual-stress datasets for direct strain-compatibility

modeling [13,51,54,57]. This reporting gap should be explicitly recognized rather than filled using generic material constants from unrelated coating systems.

5.6. Adhesion Under Tribocorrosion Conditions

Under tribocorrosion conditions, interfacial durability is affected by simultaneous mechanical and electrochemical processes. Mechanical contact may initiate coating cracks or local breaches, while electrolyte penetration through these defects promotes passive-film disruption and localized electrochemical activation. This coupled degradation pathway explains why coatings with favorable initial adhesion may fail during long-term service if the interface contains connected defects or if the coating cannot accommodate substrate deformation [8–11,13,51,54].

The degradation sequence in coated NiTi systems can be described as microcrack initiation, electrolyte penetration, passive-film breakdown, local electrochemical activation, interfacial weakening and coating delamination. For this reason, adhesion testing should ideally be combined with electrochemical and tribological measurements, particularly for coatings intended for load-bearing or contact-loaded biomedical components [8–11,13,54].

5.7. Design Implications

The reviewed data show that durable adhesion on NiTi requires simultaneous control of surface preparation, deposition parameters, microstructure, thickness, residual stress and mechanical compatibility. Monolithic ceramic coatings may offer strong barrier performance but are vulnerable to cracking when strain mismatch is large. Polymer coatings provide better compliance but may require additional optimization of wear and long-term chemical stability. Hybrid and multilayer coatings therefore remain particularly attractive because they can decouple electrochemical protection from strain accommodation and redistribute stresses across the interface [35,49,51,54,57,73,74,76].

Future studies should report adhesion data together with initial surface roughness, coating thickness, deposition parameters, residual stress, failure mode and test protocol. Without these parameters, direct comparison between coating systems remains limited and predictive modeling of coated NiTi systems under deformation and tribocorrosion conditions is not possible.

6. Interfacial Mechanics and Strain Compatibility

Mechanical compatibility between the coating and the NiTi substrate is a primary factor controlling coating durability under mechanical and tribocorrosion loading. Differences in elastic modulus generate strain incompatibility that concentrates stresses at the interface and promotes crack initiation and propagation [13,15,16,60,64,68,70–72,75,77,78].

NiTi alloys can exhibit reversible strains of up to several percent during superelastic deformation associated with stress-induced martensitic transformation [1,3]. In contrast, most ceramic coatings tolerate elastic strains typically below 1–2%, which explains their susceptibility to brittle cracking under large substrate deformation.

High-stiffness ceramic coatings constrain substrate deformation and may intensify interfacial stresses associated with martensitic transformation. This constraint effect can locally modify transformation stress levels and potentially influence fatigue behavior of the coated system [32,33]. In contrast, polymer coatings deform more readily and accommodate substrate strain with a lower risk of brittle damage, although their wear and long-term physicochemical stability may be limited [19,20,26,29,30,34].

Residual stresses introduced during deposition processes such as physical vapor deposition (PVD) or chemical vapor deposition (CVD) further affect interfacial stability. Tensile

intrinsic stresses are particularly detrimental, as they increase the driving force for crack initiation and delamination under cyclic loading [22,66,67].

The fundamental differences in deformation behavior between pseudoelastic NiTi, brittle ceramic coatings, and compliant polymer layers constitute the mechanical origin of strain mismatch in coated systems, as schematically illustrated in Figure 2. Figure 2 illustrates the fundamental differences in deformation response between the superelastic NiTi substrate and coating materials with significantly different mechanical properties. During loading, NiTi undergoes stress-induced martensitic transformation, allowing the accommodation of relatively large reversible strains. In contrast, ceramic coatings generally possess high elastic modulus and limited strain-to-failure, resulting in restricted deformation capability. Consequently, strain incompatibility develops at the coating–substrate interface when the substrate deforms more extensively than the coating layer.

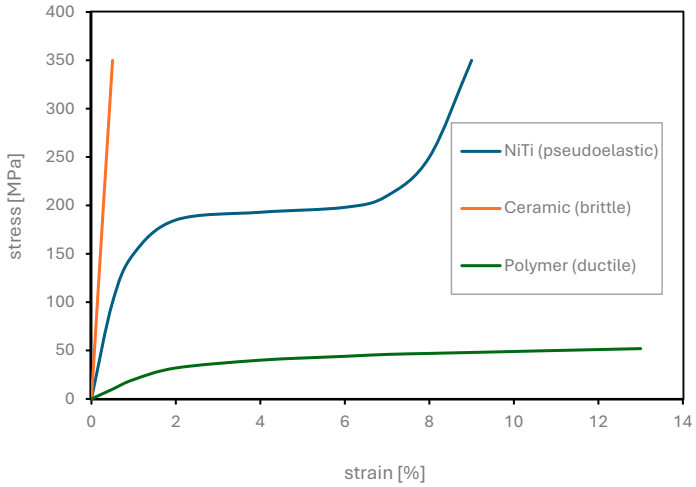


Figure 2. Comparison of deformation mechanisms governing strain compatibility in coated NiTi alloys. Original schematic illustration prepared by the authors based on the reviewed literature; not reproduced or adapted from a previously published source.

This mismatch leads to the accumulation of interfacial stresses, particularly near surface defects, pores, coating discontinuities, or geometric irregularities. Local stress concentrations may initiate microcracks within the coating or at the interface, especially under repeated loading conditions. Once initiated, these cracks can propagate through the coating thickness and ultimately lead to local delamination or spallation. The risk of such damage increases with coating thickness and stiffness because thicker and more rigid coatings store greater elastic strain energy during deformation.

Polymer coatings exhibit a fundamentally different behavior. Owing to their lower elastic modulus and higher deformability, they can accommodate substrate strains more effectively and reduce stress concentration at the interface. This enhanced compliance improves resistance to crack initiation during cyclic deformation, although it is frequently accompanied by lower hardness and reduced wear resistance. Hybrid and multilayer coating systems attempt to combine the advantages of both approaches by introducing intermediate layers with graded mechanical properties. Such architectures redistribute stresses across the interface, improve strain transfer between the coating and substrate, and reduce the likelihood of catastrophic interfacial failure during long-term service.

7. Effect of Coating Thickness

Coating thickness strongly influences stress distribution, damage initiation, and protective performance of coatings applied to NiTi alloys [66,68,71,72]. Nanometric layers

produced by atomic layer deposition (ALD) or thin-film PVD generally accommodate substrate deformation well due to limited elastic energy accumulation [13,73,79]. However, their protective capability may be insufficient under severe wear or high contact stresses.

Micrometric coatings provide improved barrier properties against corrosion and enhanced wear resistance, but they also increase the risk of stress concentration and crack formation, particularly in stiff ceramic layers such as diamond-like carbon (DLC) or metal oxides [18,65]. Increased coating thickness may additionally influence local stress states within the substrate and thereby affect martensitic transformation behavior [15,22,23,32,33].

As summarized in Table 3, no single coating thickness ensures optimal durability under all service conditions. Thin coatings favor mechanical compatibility with the superelastic substrate but offer limited tribological protection, whereas thicker coatings enhance barrier and wear performance at the expense of strain tolerance. Multilayer and compositionally graded architectures mitigate this trade-off by redistributing stresses across layers with different mechanical properties, improving adhesion and delaying damage initiation [67,74,76,80].

Table 3. Quantitative effect of coating thickness, topography and electrochemical response in representative NiTi coating systems.

Coating System	Thickness	Microstructural/ Surface Descriptor	Electrochemical Test Environment	Quantitative Corrosion Parameters	Interpretation	Ref.
ALD TiO_2 on commercial Nitinol	51.7 nm	Thin TiO_2 layer confirmed by XPS and SEM/EDX; surface particles 50 nm^{-1} µm	Simulated body fluid/Hank-type solution at 37 °C	Lowest reported jcorr = 0.16 µA cm^{-2} for commercial NiTi with TiO_2; widest passive region among tested specimens	Nanometric ALD TiO_2 can substantially improve passive stability while minimizing added coating thickness	[13]
Ag-TiO_2	NR	Island-like Ag-TiO_2 morphology; RMS roughness 98/39/23 nm depending on scan area	Ringer solution at 37 °C; EIS and cyclic polarization	Rct = (4.40 ± 0.01) × 10^5 Ω cm^2; Ecor = −0.267 V; Ebd = 1.986 V; Ep = 1.790 V	Strong barrier properties and low pitting susceptibility relative to HAp-Ag-TiO_2	[51]
HAp-Ag-TiO_2	2 µm	Compact HAp-Ag-TiO_2 layer; RMS roughness 45/20.5/15 nm depending on scan area	Ringer solution at 37 °C; EIS and cyclic polarization	Rct = (2.58 ± 0.09) × 10^5 Ω cm^2; Ecor = −0.083 V; Ebd = 2.590 V; Ep = 1.249 V	Higher adhesion and plastic deformation capacity than Ag-TiO_2, but lower Rct and higher electrochemical activity	[51]
Ag-SiO_2-TiO_2	2.02 ± 0.03 µm	Continuous SiO_2-TiO_2 interlayer with island-like agglomerates; TiO_2-rich matrix with Ag and Si	Ringer solution at 37 °C; EIS and cyclic polarization	Rct1 = (7.10 ± 0.614) × 10^3 Ω cm^2; Rct2 = (7.76 ± 0.0265) × 10^5 Ω cm^2; Ecor = −0.211 V; Ebd = 0.347 V; Ep = −0.235 V	Good resistance to generalized corrosion, but high susceptibility to localized pitting after coating damage	[54]
Parylene C (PPX-C)	5, 10, 15 µm	Semi-crystalline polymer coating; thickness increase smooths NiTi surface	Not a corrosion-centered study	Contact angle decreased from 98.4° for uncoated NiTi to 97.7°, 95.5°, and 93.5° for 5, 10, and 15 µm coatings	Polymer coating improves surface compliance and maintains superelastic behavior; electrochemical parameters NR	[57]

Rct = charge-transfer resistance; Ecor = corrosion potential; Ebd = breakdown potential; Ep = protection/repassivation potential. NR = not reported in the cited source.

These observations indicate that coating design for NiTi biomedical systems requires multi-parameter optimization, in which coating thickness must be considered alongside mechanical compatibility, residual stress state, and architectural design.

8. Ceramic Coatings

Ceramic coatings are widely applied to NiTi alloys to improve corrosion resistance and tribological performance. Titanium dioxide (TiO_2) coatings stabilize the native passive layer and reduce metal–environment interactions, leading to a significant improvement in corrosion resistance in simulated physiological solutions [12,13]. Their protective effectiveness strongly depends on coating density, microstructure, and interfacial adhesion quality.

An important factor affecting the durability of TiO_2 coatings is the development of residual stresses within the oxide layer. Residual stresses may originate from deposition conditions, thermal expansion mismatch between the coating and substrate, phase transformations, or cooling after processing. Tensile residual stresses are generally considered detrimental because they facilitate crack initiation and propagation, whereas excessive compressive stresses may promote local buckling or spallation. In thin TiO_2 layers, crack formation is often associated with stress concentration at coating defects, pores, or interfacial discontinuities. The susceptibility to cracking generally increases with coating thickness and stiffness, particularly when strain accommodation by the underlying superelastic NiTi substrate becomes limited. Although several studies have highlighted the importance of residual stresses in oxide-coated NiTi systems, quantitative stress measurements and critical fracture-load data remain insufficiently reported in the available literature, limiting the development of predictive interfacial durability models [13,37,52,73].

Diamond-like carbon (DLC) coatings offer high hardness (typically 10–25 GPa) and low friction coefficients (approximately 0.05–0.2), resulting in substantially improved wear resistance [17]. However, their high elastic modulus, often exceeding 200 GPa, limits strain accommodation and makes these coatings susceptible to microcracking or delamination under large substrate deformation [17,22,23,81,82].

Bioactive ceramic coatings such as hydroxyapatite (HAp) promote osseointegration and favorable cellular responses, which is advantageous for orthopedic applications [18,24,25,83]. Their inherently brittle mechanical behavior, however, restricts long-term durability under cyclic loading and limits their applicability in mechanically demanding NiTi components.

9. Polymer Coatings

Polymer coatings provide improved mechanical compatibility with NiTi substrates due to their low elastic modulus and high deformability. Materials such as polyurethane, polylactide, and poly(carbonate urea) urethane can accommodate substrate strain effectively and reduce the risk of crack initiation at the coating–substrate interface [19,26,57,84,85].

In addition to mechanical compliance, polymer coatings can act as diffusion barriers limiting nickel ion release and may serve as platforms for bioactive functionalization or controlled drug delivery [27,28,86]. Their primary limitation is relatively low wear resistance and gradual physicochemical degradation during long-term service, which may restrict their durability under severe tribological or tribocorrosion conditions.

Tribocorrosion

Tribocorrosion represents a critical degradation process for NiTi alloys operating in biological environments and arises from the coupled action of mechanical wear and electrochemical corrosion [8–11]. Sliding contact removes or damages the passive TiO_2 layer, exposing the substrate and increasing local electrochemical activity. Although repassiva-

tion may occur, repeated mechanical interaction often prevents the formation of a stable protective film, leading to progressive surface degradation and enhanced material loss.

In NiTi alloys, tribocorrosion behavior is further influenced by stress-induced martensitic transformation, which modifies local contact stresses and surface reactivity during cyclic loading [32,33]. Experimental studies show that tribocorrosion rates increase significantly in chloride-containing environments that destabilize the passive oxide layer [9,10,29,30,34].

Surface coatings mitigate tribocorrosion by reducing friction and limiting electrochemical exposure of the substrate. Ceramic coatings provide effective barrier protection but may crack under large strain due to stiffness mismatch, whereas polymer coatings accommodate deformation more readily but typically exhibit lower wear resistance. Hybrid and multilayer coating systems aim to combine these advantages by separating protective and compliant functions within the coating architecture [35,73,74,76,87].

The tribocorrosion process presented in Figure 3 demonstrates the strong coupling between mechanical and electrochemical degradation mechanisms occurring on coated NiTi surfaces. The process is typically initiated by mechanical contact, sliding, fretting, or micromotion, which locally damages the coating and disrupts the protective passive TiO_2 layer. Once the passive barrier is removed, the exposed substrate becomes electrochemically active and undergoes accelerated dissolution in the surrounding physiological environment.

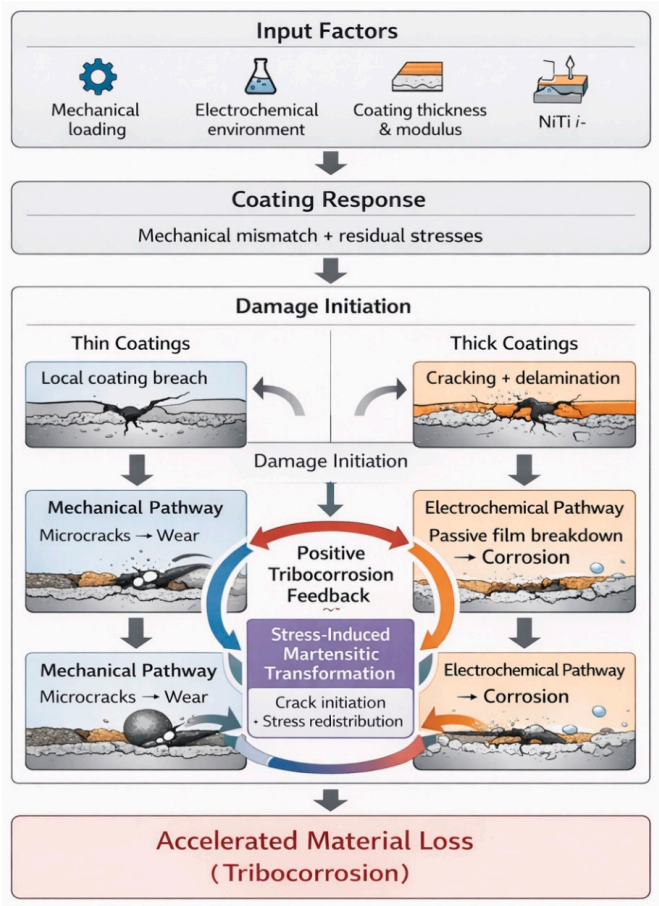


Figure 3. Mechanistic framework of tribocorrosion degradation in coated NiTi alloys illustrating coupled mechanical–electrochemical processes, thickness-dependent damage initiation, and feedback interactions governing material loss. Original schematic illustration prepared by the authors based on the reviewed literature; not reproduced or adapted from a previously published source. Blue arrows denote the predominantly mechanical damage pathway, orange arrows the electrochemical pathway, and the red/blue circular arrows the coupled positive-feedback loop between both pathways.

Simultaneously, repassivation processes attempt to restore the protective oxide film. However, under repeated mechanical loading, the newly formed passive layer may be removed before complete restoration is achieved. This creates a continuous cycle of passive film rupture, electrochemical activation, repassivation, and renewed mechanical damage. The resulting synergistic interaction produces material-loss rates that are significantly higher than those expected from wear or corrosion acting independently.

Mechanical damage additionally generates wear debris consisting of oxide fragments, coating particles, metallic debris, and corrosion products. These degradation products may further modify local contact conditions and contribute to progressive surface deterioration. In coated systems, crack formation also provides pathways for electrolyte penetration toward the coating–substrate interface, accelerating interfacial weakening and promoting delamination.

A unique feature of NiTi alloys is the contribution of stress-induced martensitic transformation. Local phase transformation alters stress distribution and contact mechanics in the near-surface region, influencing both crack propagation and passive film stability. Consequently, tribocorrosion degradation in NiTi should be regarded as a multiphysical process involving continuous interactions between mechanical damage, electrochemical reactions, tribological wear, interfacial degradation, and martensitic transformation. The positive feedback loop illustrated in Figure 3 explains why apparently minor surface defects may progressively evolve into extensive coating failure and substrate exposure during long-term service.

The coupled mechanical–electrochemical interactions governing tribocorrosion degradation in coated NiTi systems are schematically illustrated in Figure 3.

10. Comparative Analysis of Surface Modification Strategies

Surface modification of NiTi alloys requires simultaneous optimization of mechanical compatibility, corrosion resistance, tribological performance, and biological response [20,21,43,45,56,80]. The comparative characteristics of major coating classes are summarized in Tables 4 and 5.

Ceramic coatings provide high hardness and corrosion resistance, effectively stabilizing the passive layer and improving wear performance [13,14,17,18,46]. However, their elevated stiffness increases sensitivity to strain-induced damage, as reflected by dominant cracking and delamination mechanisms [13,18]. These effects may also influence martensitic transformation behavior and fatigue performance under large deformation conditions [12,13,15,16,22,23,32,33].

Bioactive ceramics such as hydroxyapatite enhance biological adhesion but remain mechanically fragile, with brittle fracture constituting the primary degradation pathway under cyclic loading [18,24,25].

In contrast, polymer coatings exhibit high deformational compatibility due to their low elastic modulus, which supports fatigue performance and minimizes transformation-related stress perturbations [26–28]. Their durability is primarily limited by wear and long-term physicochemical degradation.

From a functional perspective, coating influence on martensitic transformation, fatigue durability and strain compatibility remains particularly important. However, the available NiTi coating literature frequently reports adhesion, corrosion or biological response without providing the full set of mechanics-relevant parameters required by closed-form interfacial stress models, such as elastic modulus, Poisson ratio, coefficient of thermal expansion, residual stress and porosity. This limitation is treated here as a research gap rather than supplemented with non-system-specific estimated values.

Table 4. Quantitative comparison of coating properties applied to NiTi alloys.

Coating System	Manufacturing Method	Thickness	Roughness/Topography	Adhesion/ Mechanical Metric	Corrosion/ Electrochemical Metric	Functional Conclusion	Ref.
ALD TiO_2	ALD, 250 °C, 1100 Cycles	51.7–52.2 Nm	SEM: Tio_2 Particles 50 Nm^{-1} µm; XPS/EDX Confirmation	NR	Jcorr = 0.16 µa cm^{-2} For TiO_2/Commercial Niti	Best Suited As Thin Barrier/Passivation Layer; Low Added Thickness But Wear Resistance Not Quantified	[13]
Ag-TiO_2	EPD 40 V/3 Min + 800 °C/2 H	NR	RMS 98 Nm (10 µm Scan); Island-Like Coating	Lc3 = 20.04 ± 1.31 N	Rct = 4.40 × 10^5 Ω cm^2; Ebd = 1.986 V	Good Corrosion Resistance; Brittle Failure Tendency Under Scratch Loading	[51]
Hap-Ag-TiO_2	EPD 20 V/1 Min + 800 °C/2 H	2 µm	RMS 45 Nm (10 µm Scan); Compact Hap-Containing Hybrid Layer	Lc3 = 24.41 ± 3.71 N	Rct = 2.58 × 10^5 Ω cm^2; Ebd = 2.590 V	Better Adhesion/Plasticity And Bioactive Character; Electrochemical Activity Higher Than Ag-Tio_2	[51]
Ag-SiO_2-TiO_2	EPD 40 V/3 Min + 800 °C/2 H Vacuum	2.02 ± 0.03 µm	Island-Like Agglomerates On Continuous Sio_2-Tio_2 Interlayer; Ti 53.5 wt%, O 38.3 wt%, Ni 6.8 wt%, Ag 0.8 wt%, Si 0.6 wt%	Lc3 = 20.54 ± 1.60 N	Rct2 = 7.76 × 10^5 Ω cm^2; Ebd = 0.347 V	Silica-Containing Interlayer Improves Long-Term Barrier Behavior But Localized Pitting Remains Possible	[54]
Parylene C (PPX-C)	CVD/Gorham Process	5–15 µm	Roughness Decreases With Thickness; Contact Angle 97.7° To 93.5°	Delamination Force 231–253 N	NR	Compliant Polymer Barrier With High Adhesion Force And Retained Bending/Superelastic Response	[57]

The table intentionally avoids generic descriptors such as high/moderate/low where numerical data are unavailable.

Table 5. Quantified degradation mechanisms and failure thresholds for representative coatings on NiTi.

Coating System	Dominant Degradation/Failure Mode	Initiation Condition or Test Trigger	Quantitative Threshold/Evidence	Implication for NiTi Under Deformation	Ref.
Ag-TiO_2	Brittle spallation, arc tensile cracking, complete coating destruction	Progressive scratch loading with Rockwell indenter	Lc1 1.02 ± 0.29 N; Lc2 13.42 ± 1.14 N; Lc3 20.04 ± 1.31 N	High corrosion protection can be compromised by brittle cracking during local contact loading	[51]
HAp-Ag-TiO_2	Plastic deformation and perforation rather than immediate brittle spallation	Progressive scratch loading	Lc1 2.32 ± 0.27 N; Lc2 18.07 ± 2.09 N; Lc3 24.41 ± 3.71 N	HAp doping increases deformation tolerance and adhesion under scratch loading	[51]
Ag-SiO_2-TiO_2	Localized pitting and partial substrate exposure after corrosion damage; cohesive/interfacial scratch damage	Cyclic polarization in Ringer solution and scratch loading	Ebd 0.347 V; Ep −0.235 V; Lc3 20.54 ± 1.60 N	Coating can suppress uniform corrosion while still requiring control of defects that trigger pitting	[54]
ALD TiO_2	Porous/compact oxide-layer electrochemical response; adhesion failure not tested	Immersion and polarization in simulated physiological solution	jcorr minimum 0.16 μA cm^{-2}; oxide thickness about 52 nm	Very thin ALD layers are favorable for passivation but need independent tribological/adhesion validation	[13]
Parylene C	Potential polymer debonding under tensile delamination; no adverse bending damage reported	Tensile delamination and repeated bending cycles	Maximum delamination force 231–253 N; multiple bending cycles without reported adhesion deterioration	Compliant polymer can accommodate substrate deformation better than brittle ceramic layers, but wear/long-term hydrolytic durability still needs testing	[57]

Failure descriptions are limited to mechanisms directly reported or observed in the cited studies.

The comparative data demonstrate a fundamental design trade-off: stiffness-driven protection in ceramic coatings versus strain accommodation in polymer systems. Hybrid and multilayer architectures partially overcome this limitation by combining mechanically dissimilar layers, enabling improved tribocorrosion resistance while preserving interfacial stability [35,73,74,76].

Optimal coating design for NiTi systems therefore requires integrated multi-parameter optimization rather than prioritization of a single performance attribute.

Taken together, the data summarized in Tables 1–5 indicate that coating performance in NiTi systems is governed by the interplay between coating thickness, microstructure, adhesion strength, electrochemical stability and deformation compatibility. However, the available literature remains incomplete: many studies quantify corrosion or adhesion but do not report elastic modulus, Poisson ratio, coefficient of thermal expansion, residual stress or porosity. These gaps limit direct predictive modeling of coated NiTi systems and justify further coupled mechanical–electrochemical studies.

This multiparameter interaction framework highlights that coating durability cannot be predicted from individual material properties alone but must be evaluated in the context of coupled mechanical–electrochemical–functional behavior.

Figure 4 summarizes the evolution of coating-development strategies for biomedical NiTi alloys over the last three decades. Early studies conducted between approximately 1995 and 2005 focused primarily on understanding the corrosion behavior of NiTi and improving the stability of the naturally occurring TiO_2 passive layer. During this period, surface engineering was largely directed toward reducing nickel release and enhancing corrosion resistance in physiological environments.

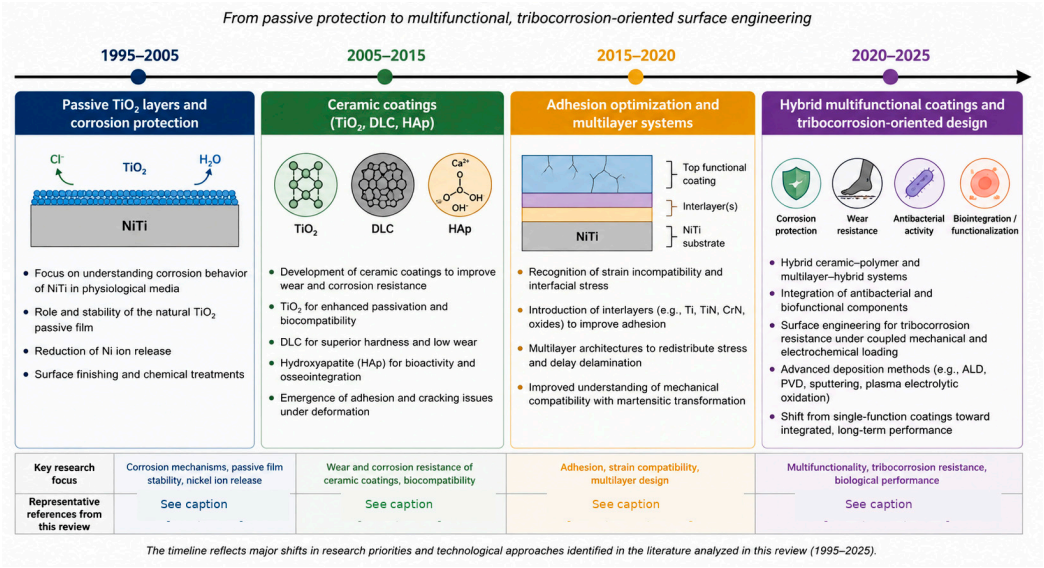


Figure 4. Evolution of coating strategies for biomedical NiTi alloys from passive corrosion protection toward multifunctional hybrid systems with enhanced adhesion durability and tribocorrosion resistance (1995–2025). Original schematic illustration prepared by the authors based on the reviewed literature; not reproduced or adapted from a previously published source. Representative literature supporting the timeline: [5,13,17–21,31–33,37,40,49–57,73,82,85,87].

Between 2005 and 2015, research activity increasingly shifted toward the application of ceramic coatings, including titanium dioxide, diamond-like carbon (DLC), and hydroxyapatite-based systems. These coatings were primarily developed to improve wear resistance, corrosion protection, and biological performance. However, growing recognition of coating cracking and delamination under deformation highlighted the importance of interfacial durability.

The period from approximately 2015 to 2020 was characterized by increased attention to adhesion mechanisms, strain compatibility, and multilayer coating architectures. Researchers increasingly recognized that coating performance depends not only on intrinsic material properties but also on stress distribution and interfacial mechanics.

Recent studies published after 2020 demonstrate a clear trend toward multifunctional hybrid coating systems combining protective, biological, antibacterial, and tribological functions. At the same time, tribocorrosion has emerged as a central design consideration, reflecting the growing understanding that coating degradation in NiTi systems results from coupled mechanical, electrochemical, and biological interactions. This evolution indicates a transition from single-function protective coatings toward integrated surface-engineering strategies designed to optimize long-term durability and functional performance simultaneously.

11. Research Gaps and Future Directions

Despite substantial progress in surface modification strategies for NiTi alloys, significant methodological and knowledge gaps remain. The comparative analysis of coating properties, degradation mechanisms, and functional effects summarized in Tables 1–5 highlights several critical research directions.

A major limitation is the scarcity of long-term fatigue studies conducted under realistic biomechanical loading conditions. Most available investigations rely on short-term or quasi-static tests, which do not adequately represent service conditions of load-bearing biomedical devices [32,33]. In particular, the influence of coatings on very-high-cycle fatigue behavior ($>10^8$ cycles) remains poorly understood.

Another important gap concerns tribocorrosion testing under fully coupled mechanical–electrochemical conditions. Although degradation of NiTi implants is inherently multiphysical, wear and corrosion processes are still frequently investigated separately [8–10]. Quantitative experimental methodologies and predictive models capable of capturing synergistic effects remain limited.

Residual stress evolution in thin-film and multilayer coatings represents an additional unresolved issue. Intrinsic stresses generated during PVD or CVD may critically affect adhesion, crack initiation, and fatigue durability, yet systematic studies linking residual stress characterization with long-term mechanical performance are scarce [13,22,23].

From a design perspective, clear criteria for optimizing mechanical compatibility between coating and substrate have not been fully established. While the trade-off between stiffness-driven protection and strain accommodation is well recognized (Tables 3 and 5), robust guidelines for tailoring graded and multilayer architectures are still underdeveloped [13,15,16,35,73,74,76].

Functional coatings introduce further complexity. Bioactive, antibacterial, and drug-delivery systems are increasingly explored; however, biological performance is often evaluated independently of mechanical durability and tribocorrosion stability [19,26–28,35,73,74,76]. Integrated assessment protocols combining biological, mechanical, and electrochemical performance are therefore needed.

Future research should prioritize multiphysical experimental and modeling approaches that explicitly couple mechanics, electrochemistry, tribology, and martensitic transformation phenomena. In parallel, the development of standardized fatigue and tribocorrosion testing methods in simulated physiological environments would significantly improve comparability across studies. Emerging surface engineering techniques, including advanced plasma-based oxidation and hybrid processes, offer promising opportunities for controlling oxide structure and residual stress states [29,30,34,37].

12. Mechanistic Framework of Coating Durability in NiTi Systems

The durability of coatings applied to NiTi alloys is governed by the interaction of multiple coupled mechanisms operating across different length scales. Based on the reviewed literature, coating degradation can be described using a mechanistic framework that integrates mechanical deformation, electrochemical reactions, tribological contact, and stress-induced martensitic transformation.

During service, cyclic superelastic deformation of the NiTi substrate transfers strain to the coating layer. When the coating exhibits significantly higher stiffness, interfacial stresses develop that can initiate microcracks at the coating–substrate interface [13]. Crack initiation typically occurs at structural defects, pores, or local stress concentrations and may propagate rapidly in brittle ceramic coatings once the elastic strain limit is exceeded [15,16,18,22,23].

Crack formation and coating damage expose the underlying substrate, increasing susceptibility of the TiO_2 passive film to mechanical removal. Local rupture of the passive layer enhances electrochemical activity and accelerates corrosion processes [8,9]. Simultaneously, sliding contact or micromotion generates tribological wear and debris, which further destabilize the surface and increase material loss rates [10,11].

In NiTi systems, stress-induced martensitic transformation modifies local stress distributions and contact conditions near the surface. Repeated transformation cycles can intensify crack propagation and fatigue damage in the coating–substrate system [29,30,32–34]. The interaction of these processes creates a positive feedback loop, ultimately leading to coating delamination, substrate exposure, and progressive degradation.

This framework demonstrates that coating durability cannot be predicted from individual material properties alone, such as hardness or corrosion resistance. Instead, reliable long-term performance requires simultaneous optimization of mechanical compatibility, coating architecture, residual stress state, and tribocorrosion resistance [35,73,74,76]. The coupled degradation pathways are summarized schematically in Figure 5.

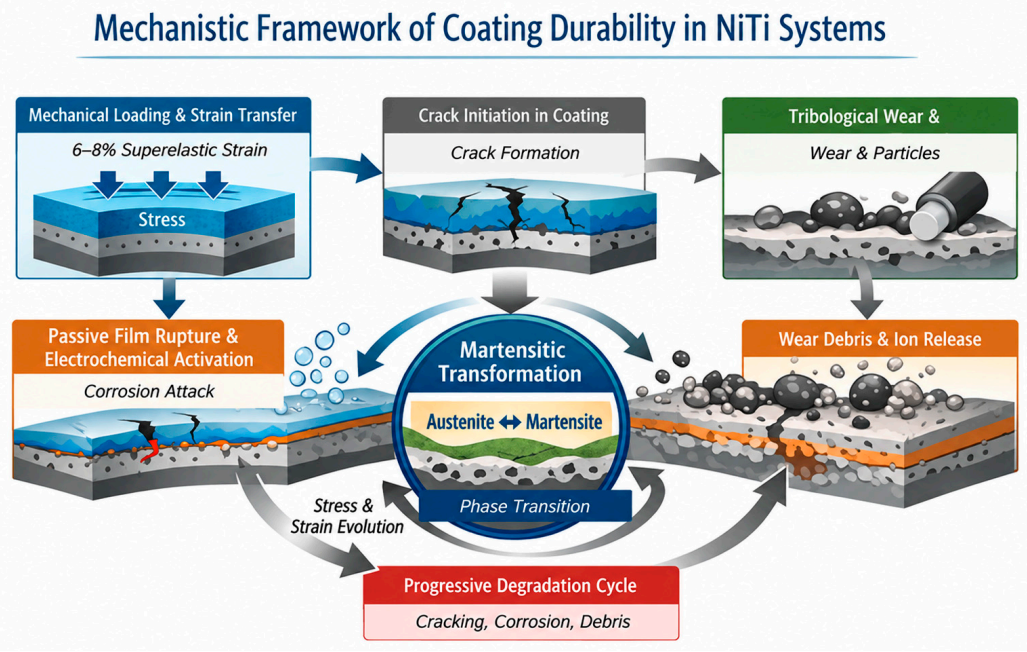


Figure 5. Mechanistic framework of coating durability in NiTi systems illustrating the coupling between cyclic deformation, coating cracking, passive film rupture, electrochemical activation, tribological wear, and martensitic transformation. Original schematic illustration prepared by the authors based on the reviewed literature; not reproduced or adapted from a previously published source. Representative literature supporting the mechanistic relationships: [3–5,8–11,13,14,17,18,32,33,37,42,46,47,73,82].

13. Conclusions

This review demonstrates that the long-term durability of NiTi alloys in biomedical applications is governed predominantly by surface-controlled degradation processes rather than by intrinsic bulk properties alone. Although NiTi exhibits exceptional superelastic and shape-memory behavior, its functional performance is strongly influenced by coupled mechanical, tribological, and electrochemical interactions occurring in the near-surface region.

Comparative analysis of ceramic, polymer, and hybrid coating systems reveals a fundamental design trade-off between stiffness-driven protection and mechanical compatibility with the superelastic substrate. Ceramic coatings provide effective barrier protection and superior wear resistance but are susceptible to strain-induced cracking under large deformation. In contrast, polymer coatings offer excellent deformational compliance while exhibiting reduced long-term tribological durability.

The durability of coated NiTi systems is therefore controlled by the interaction of multiple factors, including coating microstructure, architectural design, residual stress state, interfacial adhesion, and cyclic mechanical loading. Surface modifications may additionally alter local stress distributions and martensitic transformation behavior, thereby influencing fatigue resistance and functional stability of biomedical devices.

Among current surface engineering approaches, multilayer and compositionally graded coating architectures appear particularly promising. By redistributing interfacial stresses and decoupling protective and deformational functions, these systems offer an effective route toward improved adhesion durability under tribocorrosion conditions.

Overall, reliable coating performance on NiTi alloys requires a multiphysical design strategy that integrates mechanical compatibility, interfacial stability, and resistance to coupled mechanical–electrochemical degradation. Future progress will depend on the development of predictive durability models, systematic experimental validation, and standardized fatigue and tribocorrosion testing under physiologically relevant conditions.

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References

1. Otsuka, K.; Wayman, C.M. (Eds.) *Shape Memory Materials*; Cambridge University Press: Cambridge, UK, 1998.

2. Pelton, A.R. Nitinol fatigue: A review of Microstructures and Mechanisms. *J. Mater. Eng. Perform.* **2011**, *20*, 613–617. [CrossRef]
3. Duerig, T.; Pelton, A.; Stöckel, D. An overview of nitinol medical applications. *Mater. Sci. Eng. A* **1999**, *273–275*, 149–160. [CrossRef]
4. Rondelli, G. Corrosion resistance tests on NiTi shape memory alloy. *Biomaterials* **1996**, *17*, 2003–2008. [CrossRef] [PubMed]
5. Shabalovskaya, S.; Anderegg, J.; Van Humbeeck, J. Critical overview of Nitinol surfaces and their modifications for medical applications. *Acta Biomater.* **2008**, *4*, 447–467. [CrossRef] [PubMed]
6. Firstov, G.S.; Vitchev, R.G.; Kumar, H.; Blanpain, B.; Van Humbeeck, J. Surface oxidation of NiTi shape memory alloy. *Biomaterials* **2002**, *23*, 4863–4871. [CrossRef] [PubMed]
7. Stöckel, D.; Pelton, A.; Duerig, T. Self-expanding Nitinol stents: Material and design considerations. *Eur. Radiol.* **2004**, *14*, 292–301. [CrossRef] [PubMed]
8. Landolt, D.; Mischler, S. (Eds.) *Tribocorrosion of Passive Metals and Coatings*; Woodhead Publishing: Oxford, UK, 2011.
9. Vieira, A.C.; Ribeiro, A.R.; Rocha, L.A.; Celis, J.P. Influence of pH and Corrosion Inhibitors on the Tribocorrosion of Titanium in Artificial Saliva. *Wear* **2006**, *261*, 994–1001. [CrossRef]
10. Buciumeanu, M.; Bagheri, A.; Silva, F.S.; Henriques, B.; Lasagni, A.F.; Shamsaei, N. Tribocorrosion Behavior of NiTi Biomedical Alloy Processed by an Additive Manufacturing Laser Beam Directed Energy Deposition Technique. *Materials* **2022**, *15*, 691. [CrossRef] [PubMed]
11. Okoani, A.O.; Nand, A.; Ramezani, M. Comparative Study of the Tribocorrosion Performance of NiTiNOL60 in Acidic, Alkaline, and Saline Environments. *J. Mater. Eng. Perform.* **2024**, *33*, 13528–13542. [CrossRef]
12. Shabalovskaya, S.A.; Tian, H.; Anderegg, J.W.; Schryvers, D.U.; Carroll, W.U.; Van Humbeeck, J. The influence of surface oxides on the distribution and release of nickel from Nitinol wires. *Biomaterials* **2009**, *30*, 468–477. [CrossRef] [PubMed]
13. Rudolf, R.; Stambolić, A.; Kocijan, A. Atomic Layer Deposition of a TiO_2 Layer on Nitinol and Its Corrosion Resistance in a Simulated Body Fluid. *Metals* **2021**, *11*, 659. [CrossRef]
14. Okoani, A.O.; Nand, A.; Jiang, C.P.; Ramezani, M. Investigating the Tribocorrosion Behaviour of NiTiNOL60 Alloy in Engineering and Biomedical Applications—An Overview. *Metals* **2024**, *14*, 1334. [CrossRef]
15. Kosec, T.; Močnik, P.; Legat, A. The tribocorrosion behaviour of NiTi alloy. *Appl. Surf. Sci.* **2014**, *288*, 727–735. [CrossRef]
16. Vojtěch, D.; Fojt, J.; Joska, L.; Novák, P. Surface treatment of NiTi shape memory alloy and its influence on corrosion behavior. *Surf. Coat. Technol.* **2010**, *204*, 3895–3901. [CrossRef]
17. Roy, R.K.; Lee, K.R. Biomedical applications of diamond like carbon coatings: A review. *J. Biomed. Mater. Res. B* **2007**, *83B*, 72–84. [CrossRef] [PubMed]
18. Dorozhkin, S.V. Nanosized and nanocrystalline calcium orthophosphates. *Acta Biomater.* **2010**, *6*, 715–734. [CrossRef] [PubMed]
19. Seifalian, A.M.; Salacinski, H.J.; Tiwari, A.; Edwards, A.; Bowald, S.; Hamilton, G. In vivo biostability of a poly(carbonate urea)urethane graft. *Biomaterials* **2003**, *24*, 2549–2557. [CrossRef] [PubMed]
20. Safavi, M.S.; Bordbar-Khiabani, A.; Walsh, F.C.; Mozafari, M.; Khalil-Allafi, J. Surface modified NiTi smart biomaterials: Surface engineering and biological compatibility. *Curr. Opin. Biomed. Eng.* **2023**, *25*, 100429. [CrossRef]
21. Billah, T.; Aquib, T.I.; Dey, K. A review on surface modification of NiTinol for biomedical applications. *J. Mater. Sci.* **2024**, *59*, 19340–19379. [CrossRef]
22. Sui, J.H.; Cai, W. Mechanical and corrosion study of diamond-like carbon coating on NiTi alloys. *Surf. Coat. Technol.* **2007**, *201*, 5121–5123. [CrossRef]
23. Takeno, T.; Shiota, H.; Sugawara, T.; Miki, H.; Takagi, T. Highly adherent tungsten-containing diamond-like carbon (W-DLC) coating on a NiTi shape memory alloy under 10% tensile strain. *Diam. Relat. Mater.* **2009**, *18*, 403–406. [CrossRef]
24. Sattar, T.; Manzoor, T.; Khalid, F.A.; Akmal, M.; Saeed, G. Improved in vitro bioactivity and electrochemical behavior of hydroxyapatite-coated NiTi shape memory alloy. *J. Mater. Sci.* **2019**, *54*, 7300–7306. [CrossRef]
25. Khalili, V.; Naji, H. Developing a mechanochemical surface pretreatment to increase the adhesion strength of hydroxyapatite electrophoretic coating on the NiTi alloy as a bone implant. *Surf. Coat. Technol.* **2020**, *397*, 125985. [CrossRef]
26. Bakhshi, R.; Darbyshire, A.; Evans, J.E.; You, Z.; Lu, J.; Seifalian, A.M. Polymeric coating of surface modified nitinol stent with POSS-nanocomposite polymer. *Colloids Surf. B Biointerfaces* **2011**, *86*, 93–105. [CrossRef] [PubMed]
27. Chen, Q.; Thouas, G.A. Metallic implant biomaterials. *Mater. Sci. Eng. R Rep.* **2015**, *87*, 1–57. [CrossRef]
28. Davoodian, F.; Salahinejad, E.; Sharifi, E.; Barabadi, Z.; Tayebi, L. PLGA-coated drug-loaded nanotubes anodically grown on nitinol. *Mater. Sci. Eng. C* **2020**, *116*, 111174. [CrossRef] [PubMed]
29. Tan, L.; Dodd, R.A.; Crone, W.C. Corrosion and wear-corrosion behavior of NiTi modified by plasma source ion implantation. *Biomaterials* **2003**, *24*, 3931–3939. [CrossRef] [PubMed]
30. Haider, W.; Munroe, N.; Tek, V.; Pulletikurthi, C.; Gill, P.K.S.; Pandya, S. Surface modifications of nitinol. *J. Long-Term Eff. Med. Implants* **2009**, *19*, 113–122. [CrossRef] [PubMed]
31. Peng, M.; Zhang, Q.; Zhang, M.; Yang, Z.; Wan, Y.; Deng, X.; Luo, H. Dealloying and polydopamine/silver coating on NiTi alloy for improved antibacterial activity. *Mater. Chem. Phys.* **2023**, *305*, 127939. [CrossRef]

32. McKelvey, A.L.; Ritchie, R.O. Fatigue crack growth behavior in the superelastic and shape memory alloy Nitinol. *Metall. Mater. Trans. A* **2001**, *32*, 731–743. [CrossRef]
33. Robertson, S.W.; Pelton, A.R.; Ritchie, R.O. Mechanical fatigue and fracture of Nitinol. *Int. Mater. Rev.* **2012**, *57*, 1–36. [CrossRef]
34. Alipour, S.; Taromian, F.; Rezvani Ghomi, E.; Zare, M.; Singh, S.; Ramakrishna, S. Nitinol: From historical milestones to functional properties and biomedical applications. *Proc. Inst. Mech. Eng. H* **2022**, *236*, 1595–1612. [CrossRef] [PubMed]
35. Li, X.; Yang, Y.; Shen, H.; Zhou, M.; Huang, B.; Cui, L.; Hao, S. Research progress on surface modification and coating technologies of biomedical NiTi alloys. *Colloids Surf. B Biointerfaces* **2025**, *249*, 114496. [CrossRef] [PubMed]
36. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
37. Witkowska, J.; Sobiecki, J.; Wierzchoń, T. Advancements in Surface Modification of NiTi Alloys for Orthopedic Implants: Focus on Low Temperature Glow Discharge Plasma Oxidation Techniques. *Int. J. Mol. Sci.* **2025**, *26*, 1132. [CrossRef] [PubMed]
38. Pound, B.G. Comparison of the Passive Behavior of NiTi and CoNiCrMo in Simulated Physiological Solutions. *Corros. Mater. Degrad.* **2025**, *6*, 4. [CrossRef]
39. Sun, Y.; Rong, Y.; Zhao, Y.; Zhao, Y.; Hang, R.; Yao, X.; Chu, P.K. Electrochemical stability, corrosion behavior, and biological properties of Ni–Ti–O nanoporous layers anodically on NiTi alloy. *Corros. Sci.* **2021**, *179*, 109104. [CrossRef]
40. Goryczka, T.; Szaraniec, B.; Stodolak-Zych, E.; Kluska, S. PAN-Based Carbon Fibers Deposition on NiTi Surface. *Arch. Metall. Mater.* **2023**, *68*, 1109–1114. [CrossRef]
41. Liu, M.; Zhu, J.N.; Popovich, V.A.; Borisov, E.; Mol, J.M.C.; Gonzalez-Garcia, Y. Passive film formation and corrosion resistance of laser-powder bed fusion fabricated NiTi shape memory alloys. *J. Mater. Res. Technol.* **2023**, *23*, 2991–3006. [CrossRef]
42. López-Ortega, A.; Arana, J.L.; Bayón, R. Tribocorrosion of Passive Materials: A Review on Test Procedures and Standards. *Int. J. Corros.* **2018**, *2018*, 7345346. [CrossRef]
43. Wood, R.J.K.; Lu, P. Coatings and Surface Modification of Alloys for Tribo-Corrosion Applications. *Coatings* **2024**, *14*, 99. [CrossRef]
44. Kosec, T.; Močnik, P.; Mezeg, U.; Legat, A.; Ovsenik, M.; Jenko, M.; Grant, J.T.; Primožič, J. Tribocorrosive Study of New and In Vivo Exposed Nickel Titanium and Stainless Steel Orthodontic Archwires. *Coatings* **2020**, *10*, 230. [CrossRef]
45. Li, Y.; Zhou, Z.; He, Y. Tribocorrosion and Surface Protection Technology of Titanium Alloys: A Review. *Materials* **2024**, *17*, 65. [CrossRef] [PubMed]
46. Yang, C.; Long, T.; Yan, A.; Ma, H.; Lu, H.; Liang, L.; Cai, W. Improved corrosion resistance of selective laser melted NiTi alloys via nanosecond pulsed laser annealing treatment for biomedical application. *Addit. Manuf. Lett.* **2025**, *13*, 100306. [CrossRef]
47. *ASTM G119-09*; Standard Guide for Determining Synergism Between Wear and Corrosion. ASTM International: West Conshohocken, PA, USA, 2021.
48. Bakhtiari-Zamani, H.; Saebnoori, E.; Bakhsheshi-Rad, H.R.; Berto, F. Corrosion and Wear Behavior of TiO_2/TiN Duplex Coatings on Titanium by Plasma Electrolytic Oxidation and Gas Nitriding. *Materials* **2022**, *15*, 8300. [CrossRef] [PubMed]
49. Dudek, K.; Dulski, M.; Podwórny, J.; Kujawa, M.; Gerle, A.; Rawicka, P. Functionalization of the NiTi Surface through Hydroxyapatite/Ag–TiO_2 Hybrid Coatings. *Materials* **2024**, *17*, 604. [CrossRef] [PubMed]
50. Dudek, K.; Dulski, M.; Podwórny, J.; Kujawa, M.; Rawicka, P. Optimization of the Electrophoretic Deposition Parameters and Mechanism of Formation of Ag-TiO_2 Nanocoatings on a NiTi Shape Memory Alloy: Part I. *Coatings* **2024**, *14*, 44. [CrossRef]
51. Dudek, K.; Strach, A.; Wasilkowski, D.; Łosiewicz, B.; Kubisztal, J.; Mrozek-Wilczkiewicz, A.; Zioła, P.; Barylski, A. Comparison of Key Properties of Ag-TiO_2 and Hydroxyapatite-Ag-TiO_2 Coatings on NiTi SMA. *J. Funct. Biomater.* **2024**, *15*, 264. [CrossRef] [PubMed]
52. Witkowska, J.; Borowski, T.; Kulikowski, K.; Wunsch, K.; Morgiel, J.; Sobiecki, J.; Wierzchoń, T. Structure and Properties of Bioactive Titanium Dioxide Surface Layers Produced on NiTi Shape Memory Alloy in Low-Temperature Plasma. *Micromachines* **2024**, *15*, 886. [CrossRef] [PubMed]
53. Safavi, M.S.; Khalil-Allafi, J.; Restivo, E.; Ghalandarzadeh, A.; Hosseini, M.; Dacarro, G.; Malavasi, L.; Milella, A.; Listorti, A.; Visai, L. Enhanced in vitro immersion behavior and antibacterial activity of NiTi orthopedic biomaterial by HAp-Nb_2O_5 composite deposits. *Sci. Rep.* **2023**, *13*, 16045. [CrossRef] [PubMed]
54. Łosiewicz, B.; Kubisztal, J.; Barylski, A.; Dudek, K. In Vitro Corrosion Resistance and Mechanical Properties of Ag-SiO_2-TiO_2 Coatings Electrophoretically Deposited on NiTi Alloy. *Coatings* **2025**, *15*, 1176. [CrossRef]
55. Mroczka, R.; Słodkowska, A.; Kubacki, J. Influence of Heat Treatment of Nitinol Wire on the Properties of Nitinol/Hybrid Layer for Ibuprofen Release. *Molecules* **2024**, *29*, 5200. [CrossRef] [PubMed]
56. Safavi, M.S.; Khalil-Allafi, J.; Ahadzadeh, I.; Walsh, F.C.; Visai, L. Improved corrosion protection of a NiTi implant by an electrodeposited HAp-Nb_2O_5 composite layer. *Surf. Coat. Technol.* **2023**, *470*, 129822. [CrossRef]
57. Goryczka, T.; Szymanowski, H.; Gryń, K.; Szaraniec, B. Martensitic Transformation and Shape Memory Effect in NiTi/PPX-C Composites Dedicated to Medical Applications. *Shape Mem. Superelasticity* **2026**, *12*, 107–118. [CrossRef]

58. Bull, S.J.; Berasetegui, E.G. An overview of the potential of quantitative coating adhesion measurement by scratch testing. *Tribol. Int.* **2006**, *39*, 99–114. [CrossRef]
59. *ISO 20502:2005*; Fine Ceramics—Determination of Adhesion of Ceramic Coatings by Scratch Testing. International Organization for Standardization: Geneva, Switzerland, 2005.
60. Chen, J.; Bull, S.J. Approaches to investigate delamination and interfacial toughness in coated systems: An overview. *J. Phys. D Appl. Phys.* **2011**, *44*, 034001. [CrossRef]
61. Manam, B.U.; Langhof, N.; Sitzmann, C.; Schafföner, S. Overview of interfacial fracture toughness testing of ceramic coatings at room and elevated temperatures. *Theor. Appl. Fract. Mech.* **2025**, *140*, 105142. [CrossRef]
62. *ASTM C1624-22*; Standard Test Method for Adhesion Strength and Mechanical Failure Modes of Ceramic Coatings by Quantitative Single Point Scratch Testing. ASTM International: West Conshohocken, PA, USA, 2022.
63. Chen, Z.; Zhou, K.; Lu, X.; Lam, Y.C. A review on the mechanical methods for evaluating coating adhesion. *Acta Mech.* **2014**, *225*, 431–452. [CrossRef]
64. Walter, T.; Zareghomsheh, M.; Khatibi, G.; Popok, V.N.; Kristensen, P.K.; Boturchuk, I.; Schwarz, S. Interfacial adhesion strength of III-N heterostructures. *Mater. Des.* **2022**, *213*, 110319. [CrossRef]
65. Nix, W.D. Mechanical properties of thin films. *Metall. Trans. A* **1989**, *20*, 2217–2245. [CrossRef]
66. Abadias, G.; Chason, E.; Keckes, J.; Sebastiani, M.; Thompson, G.B.; Barthel, E.; Doll, G.L.; Murray, C.E.; Stoessel, C.H.; Martinu, L. Stress in thin films and coatings: Current status, challenges, and prospects. *J. Vac. Sci. Technol. A* **2018**, *36*, 020801. [CrossRef]
67. Ali, R.; Sebastiani, M.; Bemporad, E. Influence of Ti–TiN multilayer PVD-coatings design on residual stresses and adhesion. *Mater. Des.* **2015**, *75*, 47–56. [CrossRef]
68. Thouless, M.D. Cracking and delamination of coatings. *J. Vac. Sci. Technol. A* **1991**, *9*, 2510–2515. [CrossRef]
69. Ali, R.; Renzelli, M.; Khan, M.I.; Sebastiani, M.; Bemporad, E. Effects of Residual Stress Distribution on Interfacial Adhesion of Magnetron Sputtered AlN and AlN/Al Nanostructured Coatings on a (100) Silicon Substrate. *Nanomaterials* **2018**, *8*, 896. [CrossRef] [PubMed]
70. Bagchi, A.; Evans, A.G. The mechanics and physics of thin film decohesion and its measurement. *Interface Sci.* **1996**, *3*, 169–193. [CrossRef]
71. Volinsky, A.A.; Moody, N.R.; Gerberich, W.W. Interfacial toughness measurements for thin films on substrates. *Acta Mater.* **2002**, *50*, 441–466. [CrossRef]
72. Evans, A.G.; Hutchinson, J.W. On the mechanics of delamination and spalling in compressed films. *Int. J. Solids Struct.* **1984**, *20*, 455–466. [CrossRef]
73. Vokoun, D.; Racek, J.; Kadeřávek, L.; Kei, C.C.; Yu, Y.S.; Klimša, L.; Šittner, P. Atomic Layer Deposited TiO_2 Coatings on NiTi Surface. *J. Mater. Eng. Perform.* **2018**, *27*, 572–579. [CrossRef]
74. Mani, G.; Porter, D.; Grove, K.; Collins, S.; Ornberg, A.; Shulfer, R. Surface finishing of Nitinol for implantable medical devices: A review. *J. Biomed. Mater. Res. B Appl. Biomater.* **2022**, *110*, 2763–2778. [CrossRef] [PubMed]
75. Hutchinson, J.W.; Suo, Z. Mixed mode cracking in layered materials. *Adv. Appl. Mech.* **1991**, *29*, 63–191. [CrossRef]
76. Marchenko, E.; Baigonakova, G.; Yasenchuk, Y. Gradient crystalline coating on a biomedical TiNi alloy prepared by magnetron sputtering and annealing. *Vacuum* **2020**, *181*, 109652. [CrossRef]
77. Ye, T.; Suo, Z.; Evans, A.G. Thin film cracking and the roles of substrate and interface. *Int. J. Solids Struct.* **1992**, *29*, 2639–2648. [CrossRef]
78. Kim, J.H.; Kil, H.J.; Lee, S.; Park, J.; Park, J.-W. Interfacial Delamination at Multilayer Thin Films in Semiconductor Devices. *ACS Omega* **2022**, *7*, 25219–25228. [CrossRef] [PubMed]
79. Abbas, A.; Hung, H.-Y.; Lin, P.-C.; Yang, K.-C.; Chen, M.-C.; Lin, H.-C.; Han, Y.-Y. Atomic layer deposited TiO_2 films on an equiatomic NiTi shape memory alloy for biomedical applications. *J. Alloys Compd.* **2021**, *886*, 161282. [CrossRef]
80. Liu, Y.; Yu, S.; Shi, Q.; Ge, X.; Wang, W. Multilayer Coatings for Tribology: A Mini Review. *Nanomaterials* **2022**, *12*, 1388. [CrossRef] [PubMed]
81. Malisz, K.; Świeczko-Żurek, B.; Sionkowska, A. Preparation and Characterization of Diamond-like Carbon Coatings for Biomedical Applications—A Review. *Materials* **2023**, *16*, 3420. [CrossRef] [PubMed]
82. Peng, Y.; Peng, J.; Wang, Z.; Xiao, Y.; Qiu, X. Diamond like carbon coatings in the biomedical field: Properties, applications and future development. *Coatings* **2022**, *12*, 1088. [CrossRef]
83. Shokri, N.; Safavi, M.S.; Etminanfar, M.R.; Khalil-Allafi, J. Enhanced corrosion protection of NiTi orthopedic implants by highly crystalline hydroxyapatite deposited by spin coating: The importance of pre-treatment. *Mater. Chem. Phys.* **2021**, *259*, 124041. [CrossRef]
84. Sheiko, N.; Kékicheff, P.; Marie, P.; Schmutz, M.; Jacomine, L.; Perrin-Schmitt, F. PEEK (polyether-ether-ketone)-coated nitinol wire: Film stability for biocompatibility applications. *Appl. Surf. Sci.* **2016**, *389*, 651–665. [CrossRef]
85. Goryczka, T.; Szaraniec, B. Characterization of Polylactide Layer Deposited on NiTi Shape Memory Alloy. *J. Mater. Eng. Perform.* **2014**, *23*, 2682–2686. [CrossRef]

86. Durukan, B.K.; Sagdic, K.; Kockar, B.; Inci, F. Modifying NiTi shape memory alloys to reduce nickel ions release through ethylenediamine plasma polymerization for biomedical applications. *Prog. Org. Coat.* **2024**, *189*, 108158. [CrossRef]
87. Dudek, K.; Szaraniec, B.; Goryczka, T. Structure of multilayers deposited on NiTi shape memory alloy. *Solid State Phenom.* **2013**, *203–204*, 90–95. [CrossRef]

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