Corrosion of Fixed Orthodontic Appliances

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The orthodontic supply market is a prosperous billion-dollar industry, driven by an increasing demand for orthodontic appliances. The supremacy of metallic first-generation biomaterials is evident for manufacturing brackets, archwires, bands, and other components due to their well-recognized chemical inertness, spontaneous passivation, biocompatibility, and favorable mechanical properties combination. However, the oral cavity is the ultimate corrosion-promoting environment for any metallic material.

Keywords: bioalloys ; biocompatibility ; corrosion ; intraoral aging ; orthodontics

1. Introduction

Orthodontics may be defined as the

> "*branch of dentistry that is concerned with the supervision, guidance and correction of the growing and mature dentofacial structures. It includes the diagnosis, prevention, interception and treatment of all forms of malocclusion of the teeth and associated alterations in their surrounding structures*".
> [1]

Malocclusions—usually referred to as "*crooked*" or "*misaligned teeth*"—are a worldwide dental problem [2][3][4][5]. Technically, a malocclusion is not a disease, but rather aesthetical and/or functional misalignments between the dental arches or teeth irregularities (beyond what is considered a normal biological variation). Still, malocclusions can cause susceptibility to trauma and periodontal diseases [2][4][6][7][8][9]. Standard treatments for dental malocclusions involve removable or fixed orthodontic appliances.

Fixed appliances are, in general, more effective than removable ones—especially for more complex situations and/or for adult patients—and incorporate brackets, archwires, tubes, and/or bands, tightened by metallic or polymeric ligatures [10][11]. During treatment, a constant load is transferred from the brackets to the teeth, by using orthodontic archwires (attached to the brackets), obtaining tooth movement while adjacent bone and tissue are remodeled [12].

A standard comprehensive orthodontic treatment may last approximately 2 years [13] and involves three sequential phases: (1st) leveling and aligning; (2nd) correction of molar relationship and space closure; and (3th) detailing and finishing [14].

In contemporary orthodontics, the market supply entails a worldwide billion-dollar industry that is expected to grow in the next few years [15]. Metallic materials are still the first choice for manufacturing fixed appliances due to their balanced set of mechanical, biological, and chemical properties [16]. Up to now, the most commonly used metallic alloys include stainless steel (SS), pure titanium (Ti) and its alloys—especially nickel–titanium (NiTi)—and cobalt–chromium (CoCr) alloys. Other metallic materials can also be found in fixed orthodontic appliances, but with a lower application range.

A clinical concern during orthodontic treatments is intraoral corrosion. Always associated with metallic ion release into the oral cavity, corrosion can be intensified by dental plaque accumulation and/or mechanical actions such as friction and fatigue stress. Several important consequences of this undesirable degradation may arise, namely enamel discoloration and demineralization, hypersensitivity, inflammatory reactions and local pain, and, in more severe cases, toxicity effects [17][18][19][20][21].

The need to modify the orthodontic alloys has been identified. Current research guidelines point in two main directions: (i) to adjust the alloys' bulk composition combined with new and advanced manufacturing processes; or (ii) to modify their surface, while taking advantage of the excellent mechanical properties of the bulk. The composition and microstructure of the surface can be altered by using chemical or physical methods, either by treatment or coating deposition.

2. Metallic Corrosion

This chapter focuses on the main alloys used for the manufacturing of orthodontic appliances, the characteristics of the oral environment, and their effects on the corrosion behavior of metallic alloys.

2.1. Orthodontic Alloys

Metals and alloys thrive in the medical field and are more employed as biomaterials than any other material type [16]. Today, the major metallic alloys used in orthodontic applications include stainless steel (SS), pure titanium (Ti) and its alloys—especially the nickel–titanium (NiTi)—and cobalt–chromium (CoCr) alloys. Some of the main characteristics of these bioalloys, in comparison to human molar tooth enamel, are summarized in **Table 1**.

Stainless steels are iron (Fe)-based alloys containing at least 12% chromium (Cr) and a maximum of 1.2% carbon (C), according to the European Standard EN 10088-1 [22]. SS are outstanding materials for manufacturing brackets, bands, tubes, and ligatures [11][23][24], namely the austenitic 3xx series-AISI (American Iron and Steel Institute: 302, 303, 304L, and 316L), the precipitation hardening (PH) steels, as well as the duplex steels (SAF 2205) [10][25][26][27][28][29]. Together with Ti alloys, SS archwires are frequently used in an orthodontic treatment, especially during the 2nd and 3rd phases [30][31].

Table 1. Main characteristics of bioalloys used for manufacturing orthodontic components [26][32][33][34][35].

	Main Composition	Young's Modulus (GPa)	Yield Strength (MPa)
Human molar tooth enamel	**Calcium phosphate hydroxyapatite**	**70–115**	
Stainless steel (AISI 316L)	**Fe–Cr–Ni**	**160–187**	**960–1500**
Cobalt–chromium	**Co–Cr–Fe–Ni**	**150–217**	**830–1200**
α-Titanium	**Ti (grade 4)**	**104**	**550**
β-Titanium	**Ti–Mo–Sn–Zr**	**60–68**	**620–690**
Ti-6Al-4V	**Ti–Al–V (grade 5)**	**100–110**	**830–1070**
Nickel–titanium	**Ni–Ti**	**32–36**	**200–500**

The major advantages of these Fe–Cr alloys include their good corrosion resistance combined with their outstanding biomechanical behavior and affordable price. The key feature of the corrosion behavior is the Cr content, which is between 16 and 25 wt.% for austenitic (face-centered cubic structure, FCC) Fe–Ni–Cr alloys. The Cr element in the solid solution phase of SS alloys allows the development of the typical external protective chromium oxide (Cr_2O_3) thin film. Other bulk alloying elements of SS include molybdenum (Mo) and nickel (Ni > 8%), which improve the corrosion resistance effectiveness: while Ni promotes the formation of the FCC structure, Mo stabilizes the Cr-based passive layer.

However, some concerns regarding oral corrosion resistance, despite the presence of a small molybdenum (Mo) content, and the overall biocompatibility led to the emergence of alternatives [10][11][26][31]. The high Ni nominal content in SS alloys can cause contact dermatitis (see Section 3), which has been encouraging for the development of new Ni-"free" austenitic stainless steels (see Section 4).

CoCr-based alloys have been used in orthodontics since the 1960s for manufacturing brackets and archwires [26][31][36]. With higher Cr content (>20%), these alloys surpass the SS ones in corrosion resistance—mainly in chloride environments due to the Cr-rich oxide passive layer—and biocompatibility, with higher wear resistance [31]; yet, improved ductility and resilience may be achieved (**Table 1**). The foremost drawbacks reported in the literature include additional heat treatments to improve mechanical performance and a more complex soldering process [10]. Currently, CoCr-based wires are commercially available in four color-coded variations according to the heat treatment applied; the blue one ("soft") is the most used due to its low yield strength compared to stainless steels [26] (**Table 1**).

Ti and its alloys are among the most biocompatible materials and were introduced in orthodontics in the 1980s, gaining popularity for brackets, tubes, and archwires production [11][37]. This class of metallic materials presents outstanding mechanical properties, excellent corrosion resistance (better than SS), in addition to low density (4.5 against 7.8 g/cm^3 for SS), providing a very high strength-to-weight ratio and non-eliciting allergic responses. Commercially pure titanium (α-Ti, Grade 4) and/or Ti-6Al-4V (Grade 5) brackets and β-Ti (including titanium molybdenum alloy—TMA) archwires are examples of some Ni-free components with outstanding corrosion resistance and biocompatibility [10][38]. Ti-based brackets and tubes reduce bonding failure to enamel, whereas TMA wires are ideal for certain (but not all) orthodontic situations due to the right balance of mechanical properties (e.g., low stiffness and high stringback and formability) and weldability [10][26][31]. The low elastic modulus supports the selection of β-Ti and/or NiTi alloys (**Table 1**) for orthodontic wires. High manufacturing cost is the most negative drawback [26].

Particular attention should be given to additional Ti-based alloys, such as NiTi and Cu–NiTi alloys, due to its high Ni nominal content. Nitinol®—which stands for "Nickel Titanium Naval Ordnance Laboratory", with near-equiatomic Ni and Ti concentrations—revolutionized orthodontics since its introduction into clinical practice in 1972 [26][39][40]. Due to its distinct mechanical properties, such as shape memory (shape memory alloy—SMA) and superelasticity behavior, this class of metals is now extensively used for the manufacture of orthodontic wires. [31][37][41]. In fact, the initial leveling stage of the orthodontic treatment (Section 1) usually involves NiTi archwires [30][31]. While the shape memory effect allows for the spontaneous recovery of the component form after being subjected to deformation higher than its elastic limit (by heating), the superelasticity tolerates a constant stress as the strain increases. After the initial elastic stress region and the stress/strain release, the NiTi alloy springs back to its original shape. Thus, high elasticity, spring back, and stored energy (**Table 1**) enable low-force delivery, even when malocclusions involve extreme teeth crowding. To further increase the alloys' strength and reduce energy loss, NiTi alloys have been chemically modified by copper addition (5–6% Cu)—the Cu–NiTi alloys—by acquiring a thermally activated behavior [42][43][44]. These wires yield lower loads on the teeth and also on deformation percentage; thus, teeth movement proceeds in a more physiological manner, preventing necrosis, hyalinization areas, and the probability of root resorption [45][46]. Other elements, such as Fe and Cr, are also added to Ni–Ti-based SMA alloys to modify their mechanical properties [47]. All Ti-based alloys spontaneously passivate by generating a titanium oxide protective film that provides good oral corrosion resistance.

Other metallic alloys can be found in fixed orthodontic appliances, but with a lower application range. The use of gold (Au)—precious metal-based alloys—for instance, was widespread before 1950 due to its higher corrosion resistance compared with alternative alloys at that time [10][48]. However, high cost and poor mechanical properties (low hardness) undermine its use, even though Au-based and Au-coated aesthetic components are still available today [10][48][49][50][51][52].

2.2. Intraoral Environment

The human body is an extreme environment for any metallic biomaterial [53], and the mouth is its "portal entry" [54]—an "open ecosystem" [55] in which variations in intraoral parameters are frequent and complex, leading to a unique corrosion-promoting medium.

Human saliva—99.5% water, 0.3% proteins, and 0.2% organic compounds—plays multiple important physiological functions, not only in taste, digestion, and speech but also in teeth and tissue lubrication/protection, pH buffering, and microbiological control [56][57][58][59]. The main functions of saliva and its constituents are presented in **Table 2**. This summary intends to reflect the saliva complexity, which is further exacerbated by other factors.

Table 2. Main functions assigned to saliva and its constituents [57][58][59][60].

Function	Description	Agents
Tissue lubrication, repairing, and protection	Seromucous covering of the oral tissues. Barrier against irritants. Lubrication of hard and soft tissues, and prosthesis. Mastication, speech, and deglutition aid due to lubrication. Selective modulation of microbial adhesion to oral tissues. Modulation of dental plaque metabolism. Faster tissue repair.	Mucins and other proteins.
Clearance and pH maintenance	Acids neutralization (e.g., bicarbonate buffer). Alkalinization of dental plaque's pH through urea metabolization by its microbiome. pH modulation to prevent reaching optimal conditions for oral colonization by pathogens.	Bicarbonate, phosphate, urea, amphoteric proteins, and enzymes.
Maintenance of dental integrity	Modulation of pathogens activity to control the progression of caries and enamel damage. Maintenance of the enamel mineralization/demineralization equilibrium. The presence of fluoride in saliva enhances mineralization and forms a fluorapatite-like coating, which is more resistant to caries than the original teeth material.	Calcium, phosphate, fluoride, and several proteins (including statherin, histatins, cystatins, and proline-rich proteins).

Function	Description	Agents
Antibacterial activity	**Selective action of protein-based immunological and non-immunological agents, allowing the growth of non-cariogenic microorganisms.** **Among other mechanisms, the non-immunological action involves the adhesion inhibition of colonizers to the oral tissues, namely by aggregation (clumping).**	**Immunoglobulins, enzymes, and other proteins (including glycoproteins, staherins, agglutinins, histidine-rich proteins, and proline-rich proteins).**
Digestion, taste, and smell	**Besides lubricating food and tissues, saliva starts the chemical oral digestion, namely by the initial action of the α-amylase (converting complex carbohydrates into simple sugars).** **The hypotonicity of saliva (low sodium, glycose, bicarbonate, and urea levels) regarding plasma, which enhances the dissolution of the substances.** **The presence of proteins (such as gustin) is necessary to the growth of gustatory buds.**	**α-amylase, gustin, lipases and other proteins.**

Proteins and glycoproteins from saliva rapidly adhere to teeth enamel and any other surface placed inside the oral cavity to form a thin layer (70–100 nm), making them an important natural lubricant and oral protective film [57][61][62]. The most relevant chemical components of saliva include inorganic ions (e.g., N^+, K^+, Cl^-, F^-, CHO_3^-, PO_4^{3-}, …), antimicrobial factors, nitrogenous compounds, enzymes, immunoglobulins, albumin and other proteins, and glucose, among others [54][57][59][60][63]. Moreover, the chemical composition, temperature, and pH of human saliva vary between individuals and along the course of the day (circadian rhythms), also depending on the person's lifestyle, diet, and health/disease conditions [60][61][64][65][66][67][68].

Intraoral mean temperature usually ranges around 33–37 °C [64], but abrupt variations up to 65 °C can occur (e.g., drinking a hot coffee after eating an ice cream or drinking a glass of ice water) [65][69]. The pH of non-stimulated saliva—i.e., without consuming food or drinks—usually varies between 6 and 7, but may also oscillate from 5.3 to 7.8 [54][64][70]. A pH value below 5.5 facilitates the development of dental caries [70][71][72]. An acidic diet can also reduce intraoral pH to 3, for instance, due to acidic soft drinks and fruit juices (pH from 1 to 6) [56][70][73][74]. Another possible contributor to salivary pH fluctuation is regurgitated stomach acid, which has a typical pH value of 1.2 [56]—one of the intraoral problems of bulimic people and oncological patients.

The oral environment is additionally ideal for the inevitable proliferation of microorganisms. So far, over 700 bacterial species have been identified, as well as numerous fungi and viruses [54][55][61][75]. The oral microbiota co-evolved with humans in a mutualistic or even symbiotic manner: While the host provides excellent physiochemical and nutritional conditions, microorganisms (especially bacteria) play important physiological roles, including digestion, oral mucosa cell differentiation, and protection against exogenous pathogens [76][77].

Planktonic (i.e., non-attached, free-floating) bacteria are 1000 times more vulnerable to antimicrobials than when aggregated. Therefore, some species—the primary colonizers—soon physically associate with and then adhere to the glycoprotein-based film over the teeth and biomaterials' surfaces. Other bacterial species adhere and proliferate along with primary colonizers, forming microcolonies imbedded in an extracellular polysaccharide matrix. At this point, an oral biofilm (the dental plaque) grows: Complex groups of microcolonies positively interact with each other and even form a "primitive circulatory system" [55]. The grown (mature) oral biofilm is therefore advantageous to its inhabitants by providing nutrients to and protecting both aerobic and anaerobic colonizers—even against drugs, antimicrobial factors from saliva, and phagocytic cells [55][77][78].

While dental plaque consumes remaining food inside the mouth and protects the teeth against mechanical and chemical injuries (e.g., enamel demineralization), caries and periodontitis may occur if the host/dental plaque relationship is disturbed [61][76][77]. Some species are pathogens, and the microbiological activity of dental plaque releases several by-products into the oral cavity that can modify the chemical composition, oxygenation, and oral pH values [61][76][77]. Saliva and self-cleansing by the cheeks and tongue can naturally control biofilm growth to a certain extent. Nevertheless, oral hygiene procedures are crucial for removing dental plaque, including mechanical brushing with fluoride-containing toothpastes and mouth rinsing with fluorinated mouthwashes and elixirs [66][76][77][79][80].

In short, the intraoral environment is a highly dynamic and complex system—an ultimate degradation-promoting scenario for any biometallic material. Corrosion is a necessary (but not sufficient) condition for causing adverse biologic effects during the use of fixed orthodontic appliances.

2.3. Corrosion of Metallic Alloys

Metallic corrosion can be expressed as a "*physicochemical interaction between a metal and the environment that results in changes in the properties of the metal, and which may lead to significant impairment of the function of the metal, the environment, or the technical system, of which these form a part*" [81].

In an aqueous environment, such as the intraoral cavity, corrosion initiates through electrochemical reactions in the metal/solution interface, involving the anodic dissolution of the metal, Me to $Me^{2+}aq$ (oxidation, Equation (1)), and the cathodic reduction of an oxidant from the solution, $Oxaq$ to $Red(e^{-}_{redox})aq$ (reduction, Equation (2)), that is [82]:

$$Me \rightarrow Me^{2+}_{aq} + 2e^{-}_{metal} \tag{1}$$

$$2Ox_{aq} + 2e^{-}_{metal} \rightarrow 2Red\left(e^{-}_{redox}\right)_{aq} \tag{2}$$

The general charge-transfer reaction for a divalent metal can be written according to Equation (3) [82]:

$$Me + 2Ox_{aq} \rightarrow Me^{2+}_{aq} + 2Red\left(e^{-}_{redox}\right)_{aq} \tag{3}$$

Dissolved oxygen is usually the cathodic reactant—e.g., according to Equation (4)—with the production of hydroxide ions. However, other mechanisms could be more relevant under acidic conditions since protons may accept electrons produced during the anodic reaction. Typical cathodic reactions under low pH include both Equations (5) and (6), producing water or hydrogen gas, respectively [16][31][78].

$$\frac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-} \tag{4}$$

$$O_2 + 4H^{+} + 4e^{-} \rightarrow 2H_2O \tag{5}$$

$$2H^{+} + 2e^{-} \rightarrow H_2 \tag{6}$$

The end result of corrosion is the release of metallic ions into the electrolyte, whose extent depends on the electrolyte's nature, including its chemical composition, dissolved oxygen, and pH [31][83]. Moreover, the type of metal or alloy, its manufacturing process, and surface finishing will also influence corrosion [17][28][83][84][85][86].

Most bioalloys—mainly those containing Cr and Ti—rely on the spontaneous formation of a surface protective film. This thin oxide-based layer (some nm thick) may act as a barrier to the movement of ions—a passive film—protecting the metallic substrate against additional electrochemical corrosion [31][81][82]. Passivation is well established, being a spontaneous equilibrium of precipitation and dissolution of ions, with both active and passive films in contact with the electrolyte [87][88].

2.4. Oral Corrosion Forms

Intraoral degradation of metallic appliances is inevitable. Until today, nine basic corrosion types have been reported: uniform, galvanic, crevice, pitting, intergranular, selective leaching, stress, erosion, and microbiologically induced corrosion (MIC), which will be briefly addressed as follows.

2.4.1. Uniform Attack

Uniform corrosion is recognized as general corrosion. This degradation form seems to occur uniformly over the entire surface due to surface electrochemical reactions, almost at the same rate [69][81]. It is the most common type of oral corrosion, affecting all metallic materials at different rates [83], but sometimes it is difficult to detect—only when a significant amount of material is dissolved. All parts of a metallurgical and compositionally uniform surface should be accessible to the electrolyte (saliva) [18].

2.4.2. Galvanic Corrosion

Galvanic corrosion is observed when two different metallic surfaces—with different corrosion potentials—are joined or sufficiently close in an electrolyte solution by establishing a galvanic coupling. The more electropositive (less noble) metal or alloy becomes the anode and preferentially corrodes [16][19][69][81][83].

In orthodontics, contact between dissimilar metallic surfaces might occur in two situations: By simple contact [18][89] or through bonding processes [10][18][90]. In the first case, bracket/wire interactions are inevitable during orthodontic treatment with fixed appliances. Predictably, in certain combinations, such as in the so-common NiTi wire/SS bracket, galvanic corrosion is susceptible to occurring [18], especially in a fluoride-rich environment [89]. Recent research work [48] reported no evidence of galvanic coupling between SS lingual brackets and SS archwires, but the authors suggested caution when using fluoride-containing products during fixed orthodontic treatment with SS brackets and NiTi archwires.

Different parts of brackets or posted archwires are often made of dissimilar alloys, leading to galvanic corrosion [91]. Furthermore, brazing alloys can be used during the manufacturing of orthodontic components [10][18]. Mechanically active welding joints [83] may be reactive, increasing galvanic corrosion susceptibility accompanied by toxic metallic ion release, particularly for silver (Ag)-, copper (Cu)-, and zinc (Zn)-based welding materials [18][92][93]. A recent in vitro study [94] demonstrated that Ag ion release from Ag-soldered SS bands was an order of magnitude higher than other non-soldered SS orthodontic appliances. The authors assigned this effect to the manufacturing process used (welding).

It is generally accepted that galvanic cells can also occur in different locations of the same metallic surface due to non-uniform surface finish (e.g., roughness and chemical composition) and mechanical properties (e.g., work hardening) or even dissimilar properties of the electrolyte (pH and chemical composition) [83]. In the oral cavity, saliva is the main electrolyte, but extracellular fluids such as blood or gingival fluid are also present. Galvanic currents may take place due to the contact of the metallic surface to different biological fluids [61].

2.4.3. Crevice Corrosion

Crevice corrosion is a localized attack occurring in or near constricted places (crevices) formed by two surfaces, of which at least one is metallic [81]. This leads to a local enhancement of aggressive species and depletion of oxygen, in addition to the consequent acidification of the crevice solution due to the hydrolysis of the dissolving metal ions. Generally, metallic materials that show an affinity to pitting also suffer from crevice corrosion. The main causes include differences in metallic ions, fluoride concentration, or oxygenation between the crevice and its surroundings [17][69], associated with a pH decrease and a chloride ion concentration increase [10][18], which deteriorate the protective passive layer—especially on SS alloys [95].

Elastomeric or metallic ligatures are frequently used to fix orthodontic archwires to brackets, establishing ideal sites for crevice attack on brackets [90] (including on 316L SS alloy): Deep craters, fissures, and pores have been detected after long intraoral exposure, as well as extensive deterioration and perforation of the resin-fixed bracket base [17][19][69]. Daems et al. [96] also noticed this type of corrosion at regions of bracket/archwire contact or with plaque and food remnants. Other factors that reportedly cause crevice corrosion comprise the recycling process of the components [18]—not recommended in several countries—surface defects or irregularities [83][96]—including those caused by handling the components by the orthodontist during treatment—and the presence of welding areas [38][97].

2.4.4. Pitting Corrosion

Pitting corrosion is a localized type of corrosion that initiates on metallic surfaces when the protective passive film disrupts due to mechanical and/or electrochemical attack [81][88], leading to the formation of pit holes and/or cavities. This attack has been associated with other corrosion types [95][98], such as the one caused by the well-adherent biofilm that forms during orthodontic treatments. Aggressive ions in saliva, such as chlorine and fluoride [18][31][99]—especially under acidic conditions [100][101][102]—and food additives, such as certain spices [103][104], effectively damage surface protective oxides. Manufacturing defects on orthodontic metallic components may also increase pitting corrosion susceptibility for both SS and NiTi alloys [17][18][19].

The main strategy to improve the pitting resistance of SS alloys is to increase the Cr and Mo nominal content. However, the presence of non-metallic inclusions, such as manganese sulphide (MnS), is of major importance since pits usually initiate at these precipitates [105][106][107]. Usually, the CoCr-based alloys are resistant to pitting; the dissolution of the protective Cr_2O_3 layer into soluble ions (CrO_4^{2-}) takes place by oxidation at potentials below the oxygen evolution range [108].

2.4.5. Intergranular Corrosion

As the name suggests, intergranular corrosion occurs in microstructural planar defects along grain boundaries or in the immediate near zones, with minimal or no attack on the alloy grain itself [81][95]. The net result is an alloy fracture along these grain boundaries. SS alloys—used for manufacturing orthodontic brackets and archwires—are particularly vulnerable to this corrosion form, leading to surface staining, weakening the mechanical behavior (strength and ductility), or even failure [93][104]. Special attention should be given to heat treatment of steels [26] (or brazing/welding [83][97][109]—termed weld decay). For a prolonged period above the sensitization temperature [17][18], the formation of small precipitate particles of chromium carbide ($Cr_{23}C_6$) occurs [95]. Two major consequences arise: the SS brittleness increases and its corrosion resistance decreases, both due to the Cr-depleted zone adjacent to the grain boundary [26][83].

2.4.6. Selective Leaching

Selective leaching or dealloying is found in solid solution alloys, such as Ni–Cr-based or binary alloys containing calcium (Ca) and zinc (Zn) [16], occurring when one element is preferentially removed during the corrosion process [69][95]. This preferential release of a more reactive element from an alloy, regardless of its chemical composition [81], can occur in vivo [16][17]. Still, the effect of selective leaching seems negligible in dentistry [16][69].

2.4.7. Stress Corrosion

Stress corrosion, sometimes termed stress corrosion cracking (SCC), develops due to the influence of both applied tensile stress and a corrosive environment [17][83]. Some alloys that are virtually inert in a particular corrosive medium can become susceptible to this type of corrosion when under loads. This can seriously compromise the mechanical integrity of the material, and failure may eventually occur under low stress levels (compared with alloys in non-corrosive environments) [69][81][95]. Nitinol archwires bonded to brackets are exposed to compressive and tensile stress and might fracture during orthodontic treatment [18][110].

2.4.8. Erosion Corrosion

Erosion corrosion refers to the deterioration of a metallic material due to mechanical abrasion or wear with the combined action of the chemical attack of the corrodent fluid motion. Three subtypes are well known: Erosion, cavitation, and fretting [95]. In orthodontics, fretting corrosion is the most relevant form [69], due to the slight relative motion (vibration and slip) of two contacting metallic surfaces under load [81][95]. Surfaces of both archwires and bracket slots experience load and may undergo a cold-welding phenomenon. In addition, the required small displacements could disrupt the passive films and, consequently, increase corrosion susceptibility (e.g., by pitting) [17][18][83].

2.4.9. Microbiologically Induced Corrosion

As previously mentioned, oral microorganisms can directly or indirectly degrade metallic materials in vivo, either by metabolizing metal from the surface or by modifying the surrounding electrolyte with their metabolic by-products, respectively [83]. This form of corrosion is known as microbiologically induced corrosion (MIC) [61][95][111]. Zarasvand and Rai [78] extensively studied the MIC mechanisms, while Mystkowska et al. [61] described the intraoral process. Accordingly, oral biofilms create differential concentration cells on the metallic surfaces of three main types: oxygen concentration cells, metal concentration cells, and active–passive cells.

Oxygenation cells appear due to a non-uniform biofilm layer—in terms of thickness, ratio of aerobic (oxygen-consuming)/anaerobic microorganisms, or due to the presence of layers of corrosion products—that cause differences in oxygenation throughout the surface. Regions with high oxygen concentrations favor cathodic reactions, and the metallic surface below becomes the cathode. Conversely, in a poorly oxygenated environment, the anodic reaction is enhanced (Equation (1)), and the surface becomes the anode and corrodes. Differences in metallic ion concentration on different sites also occur due to the nature of the extracellular matrix, which has diverse composition and functional groups with different affinities to metallic ions. Under biofilm regions with low affinity to metallic ions, cathodic reactions further progress, whereas anodic dissolution of the metal increases under high-affinity biofilm sites. Finally, if a dense biofilm layer is mechanically or chemically disrupted, the exposed metallic surface corrodes (the anode), while biofilm-covered regions behave as cathodes [61][78]—active–passive cells [81].

Certain anaerobic microorganisms, such as sulfur-reducing bacteria (SRB), release corrosive metabolic products that degrade metallic alloys. The SRB can produce hydrogen gas (H_2), hydrogen sulfide (H_2S), and sulfur difluoride (F_2S, a strong local cathode), while other Gram-negative bacteria release butyric acid ($C_4H_8O_2$) and carbon dioxide (CO_2) [61][78][95]. Besides weakening and retarding the passivation mechanism of the metallic surface, H_2S is highly toxic to cells [112] and reacts with metals to form metal sulfides and atomic hydrogen. Metal sulfides may precipitate on the surface, generating new active–passive cells, while released atomic hydrogen can cause SCC [61][78][81].

3. Harmful Effects and Clinical Implications

The main consequences of intraoral aging of orthodontic metallic alloys are briefly presented in this chapter, namely the release of metallic ions into the oral cavity, the friction effect between components, and the consequences of using fluoride-based products during treatment with fixed orthodontic appliances.

Aging of metallic alloys is an important issue in orthodontics since both structural and morphological modifications can occur and thus negatively affect the normal clinical treatment progression. Corrosion of metallic surfaces and the presence of biofilm promote metallic ion release and roughness, which may increase friction between brackets and archwires [113][114][115][116][117] and extend the treatment time. Another pointed aging implication is the friction enhancement between the appliance and the mucosa, which causes oral mucosa lesions (from minor wounds to large ulcers), resulting in patients' pain and discomfort [56][118][119][120]. Moreover, aging decreases the resistance to fracture of metallic alloys under repeated cyclic loading [19][115]—fatigue—and could lead to premature failure of archwires [83][121] ruining the in vivo function of the biomaterial.

3.1. Release of Metallic Ions

Corrosion processes ultimately cause the release of metallic ions and particles into the oral cavity [17][87][122][123], which may interact with oral tissues and move to the gastrointestinal tract; even so, their impact on health is not yet fully understood [31][61][83][124]. Biocompatibility concerns raised among clinicians and researchers as hazardous species such as nickel, chromium, cobalt, copper, and vanadium (Ni, Cr, Co, Cu, and V, respectively) can be released from metallic appliances [16][18][123][125][126][127]. Back in 1975, Samitz and Katz [128]—who reviewed data related to Ni released from implanted prostheses—concluded that solubilized metal was found in tissues near implants in laboratory animals.

Multiple researchers have been trying to quantify the release of metallic ions from orthodontic appliances to assess if the concentrations can reach toxic levels for humans, both in vitro and in vivo [123][129][130][131].

The first study found dates back to 1991, by Gjerdet et al. [132], and measured the Ni and Fe contents in patients' saliva up to 3 months of usage. The authors found an initially higher salivary metal content that decreased over treatment time, but values were small when compared with those from dietary intake. Nonetheless, they were already alerted to the large interindividual variability found, as well as to Ni-sensitive patients [132].

Through time, Ni and Cr concentrations are almost always focused, but most studies concluded that the salivary metallic ion concentration is well below toxicity levels. In fact, dietary studies conducted in different countries obtained a daily intake of nickel between 100 and 300 µg/day from food and drinking water. Consuming Ni-enriched food (e.g., processed food) may increase this value up to 900 µg/day [83][133][134][135][136][137][138][139]. Haber et al. [140] estimated a toxicity reference value for Ni-sensitized populations of 4 µg Ni/kg of body weight per day, in addition to Ni in food. Concerning chromium, an average daily intake of 50–280 µg has been proposed [83][141]. However, some authors who analyzed different matrixes (oral mucosa cells, dental plaque, bone, gingiva, hair, and internal organs) found evidence of bioaccumulation that may provoke toxic effects, including DNA damage. In fact, Eliades and Athanasios [17] argued that in vivo studies measuring urinary or serum concentrations of metallic ions in orthodontic patients may give falsely lower Ni levels due to its accumulation in an organ. Further research should therefore persist.

Among the metallic ions released into the oral cavity, Ni raises special health concerns and has been systematically studied [16][133][137][138][140][142][143][144][145][146][147][148], including in orthodontics [122][123][147][149][150][151][152][153][154][155][156][157][158][159][160][161]. The European Union (EU) currently forbids the use of Ni [162]:

- "in any post-assemblies which are inserted into pierced ears and other pierced parts of the human body unless the rate of Nickel release from such post-assemblies is less than 0.2 µg/cm^2/week (migration limit)";
- "in articles intended to come into direct and prolonged contact with the skin (…) if the rate of Nickel release from the parts of these articles coming into direct and prolonged contact with the skin is greater than 0.5 µg/cm^2/week";
- "in articles referred to in point 2 where these have a non-nickel coating unless such coating is sufficient to ensure that the rate of nickel release from those parts of such articles coming into direct and prolonged contact with the skin will not exceed 0.5 µg/cm^2/week for a period of at least two years of normal use of the article" [162].

Unfortunately, biometallic alloys lie outside of this EU regulation regarding this matter. The *American Academy of Pediatrics* also expressed concerns regarding the use of Ni-containing alloys, urging the adoption of regulations similar to the EU nickel directive [147]. Dental biomaterials must still comply with several standards and regulations [163].

This transition metal (Ni) is a well-known allergen [164][165], a strong immunologic sensitizer capable of inducing delayed hypersensitive reactions [148][166], triggering cytotoxic, carcinogenic, and mutagenic effects [123][143][167][168], and affecting several cellular functions by long-term exposure to a small amount [123]. Moreover, emphasis has been given to Ni-induced genetic effects, including DNA damage and the inhibition of enzymes involved in DNA reparation [123][159]. The International Agency for Research on Cancer (IARC) classifies Ni (II) and its compounds as carcinogenic or potentially carcinogenic to humans [144].

Chromium is another well-known toxic element. Between the two most stable oxidation states, Cr(III) and Cr(VI), its hexavalent form is toxic and exhibits mutagenic, cytotoxic, and carcinogenic effects in humans [123]. Reportedly, both oxidation states were found in vitro after the corrosion of SS orthodontic brackets in artificial saliva [169].

Ni carcinogenicity, genotoxicity, and allergy are controversial in orthodontics [83][170][171][172][173][174][175][176]. Nonetheless, released Ni from orthodontic components can accumulate in the oral mucosa cells and decrease cell viability [159], while systemic toxicity should not be ignored [177]. Moreover, Kochanowska et al. [178] showed the in vivo effect of long-term exposure to metal orthodontic appliances on both the metallothionein gene expression and the induction of protein synthesis by using animal models (pigs).

Several subtle to severe intra- and/or extra-oral symptoms of allergic reactions to nickel have been reported due to the use of metallic appliances [20][126][171][179][180][181][182][183][184][185]. Symptoms include burning sensation, stomatitis, angioedema, severe gingivitis without dental plaque, gingival hyperplasia, generalized urticaria, and widespread eczema [20][126][182][185][186][187][188]. Besides discomfort and pain for patients, orthodontists may need to replace high Ni-containing components, interrupt the treatment, and/or refer the patient to an allergologist or other specialist for further examination [180][182][183][184].

Ni allergy—namely extreme hypersensitive reactions—is (fortunately) rare in orthodontics [21][170][185], but may be ineffectively diagnosed: Subtle signs are easily misinterpreted as mimicking mechanical injuries or microbiologic activity [83][171][181][189]. Schuster and colleagues [171] reported allergy symptoms related to the presence of fixed appliances during treatment without intraoral signs. Corrosion products induce enamel demineralization, metallic ion incorporation, and color change [190], as well as pain and swelling of oral soft tissues, leading to secondary infections [18]. Pazzini et al. [191] concluded that patients treated with Ni-“free” (0.5–4% Ni) appliances had better gingival health and smaller blood changes when compared with those wearing conventional metallic components (13% Ni). Another possible negative effect is the increase in antibiotic resistance of some bacteria exposed to metals and their potential transfer to medically relevant pathogens [83].

For further comprehension of the toxic effects of metallic ions released during a fixed orthodontic treatment, the reading of the outstanding review works conducted by Martín-Caméan and colleagues [123][192], and by Downarowicz and Mikulewicz [193], is recommended.

3.2. Friction in Orthodontics

Resistance to sliding is present when two surfaces come into contact with each other (e.g., bracket/wire and wire/ligature) [12][26], which is clinically relevant in orthodontics since reduced resistance to sliding can decrease treatment time [194]. Kusy and Whitley [195][196] partitioned resistance to sliding into three components: (i) Friction, “*a force that opposes every action that an orthodontist takes to move the teeth*”; (ii) binding, when the angle between the bracket slot and the archwire is high enough to promote contact between the bracket corners and the archwire; and (iii) notching, when a permanent deformation of the wire (or bracket) occurs [194][195][196][197][198].

Saliva is the natural intraoral lubricant by forming a protective pellicle [56][57][58][59]—a double layer of proteins [61]—on any material surface and, therefore, reducing the dynamic coefficient of friction [62][199]. While biofilms might have a protective role [54][78][200], microbiological activity most likely contributes to surface degradation by inducing corrosive microcells, rupturing the biofilm, and roughening the appliance surfaces [61]. These effects increase friction, wear, and metallic ions released from the bracket/wire contact pair.

3.3. Oral Hygiene with Fluoride-Based Products

Functional and aesthetic success is essential in orthodontics, but patients must comply with proper oral hygiene during treatment to avoid tooth demineralization and white spot lesions [79][89][201]. Fixed appliances make this task difficult, as the number of oral bacteria related to gingivitis increases shortly after their oral placement [201]. In fact, dental plaque accumulates in several regions, namely in the gingival areas or behind the archwires (e.g., on the bracket slots) [17][96][98][116][202]. To fight dental plaque, orthodontists prescribe fluoride-containing toothpastes, mouth rinses, gels, and varnishes to further control its accumulation and growth, enhance enamel integrity, and prevent dental and gingival diseases [60][79][203].

The downside of using these fluorides is the increased corrosion susceptibility of metallic alloys [18][31][204][205][206][207][208][209][210][211]. Fluoride ions (F^-)—combined with mechanical brushing—easily degrade the protective oxide layers of both SS and Ti-based alloys (see Equations (8) and (9)), increasing localized and general corrosion, promoting metallic ions release [205][212], and negatively impacting their mechanical and surface properties [30][31][206][208][211][213][214][215]—especially at low pH [101][102] and under the simultaneous presence of chloride ions [216].

Walker et al. [30] reported reduced unloading mechanical properties of SS and β-Ti archwires when exposed to neutral or acidulated prophylactic fluoride gels, which may prolong the orthodontic treatment time. On the other hand, Sufarnap and colleagues [44] reported an increase in both surface roughness and Ni and Cu release from Cu–NiTi archwires in NaF solution in vitro without a significant change in the deflection force.

Corrosion of SS bands and brackets [99][102][217][218] also increases in the presence of fluoride ions. Chantarawaratit and Yanisarapan [218] argued that acidulated phosphate fluoride gel should not be used in patients wearing fixed metal-based orthodontic appliances.

Since these SS components are the support for NiTi or Cu-NiTi archwires, galvanic coupling risk increased during the 1st orthodontic treatment phase (leveling/aligning) with possible mechanical and/or biocompatibility-related adverse consequences [89][93][213].

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