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Bonding on Unusual Enamel Surfaces: A Comprehensive Review

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Abstract: Orthodontic bonding was revolutionised by Buonocore's introduction of the acid-etch technique in 1955, which replaced cumbersome banding with direct micromechanical attachment of brackets to enamel. While bonding to intact enamel is now highly predictable, the growing number of adult patients seeking orthodontic treatment has increased the frequency of bonding to unconventional substrates, including ceramic and zirconia restorations, composite and amalgam fillings, gold and stainless-steel surfaces, fluorosed and hypoplastic enamel, bleached enamel, and dentin or cementum. These substrates differ from sound enamel in composition, surface energy, and reactivity, and therefore respond poorly to conventional phosphoric-acid etching. This review synthesises current literature on the principles, materials, and substrate-specific protocols used for bonding to unusual surfaces, including hydrofluoric acid–silane systems for silica-based ceramics, airborne-particle abrasion with MDP-containing primers for zirconia and metals, adhesion promoters and deproteinization for altered enamel, and acetone wet-bonding for dentin. Recent innovations such as universal adhesives, nano-filled resins, and laser-assisted bonding are also discussed. Evidence indicates that reliable bonding to unusual surfaces requires accurate identification of the substrate, individualised surface conditioning, and meticulous clinical technique, enabling predictable bracket retention while preserving enamel and restorative integrity

I. Introduction

The introduction of acid-etch bonding by Buonocore in 1955 marked a turning point in adhesive dentistry, demonstrating that conditioning enamel with phosphoric acid enhances resin adhesion by increasing surface roughness and surface energy[1]. Acid etching selectively dissolves enamel prisms, creating microporosities into which low-viscosity resin penetrates to form resin tags, thereby producing micromechanical retention rather than true chemical bonding[2]. This discovery paved the way for direct bonding techniques that eliminated the routine use of orthodontic bands and became a clinical standard through the 1980s[3].

Successful orthodontic bonding depends on the interaction of three elements: bracket-base design, tooth-surface condition, and the properties of the bonding material[4]. Ideally, the adhesive-bracket bond is stronger than the adhesive-enamel bond so that debonding failure occurs at the enamel interface, minimising damage to the bracket[4]. Conventional bonding is designed for intact enamel; however, contemporary practice increasingly requires bonding to ceramic restorations, porcelain crowns, amalgam and composite restorations, gold surfaces, fluorosed or hypoplastic enamel, dentin, and zirconia-based restorations[5]. Such substrates differ markedly from enamel in surface morphology, chemical composition, and moisture behaviour, and inadequate bonding may cause bracket failure, prolonged treatment, and enamel damage.

The growing demand for adult orthodontic treatment has increased the prevalence of patients with existing restorations and altered enamel, making a working knowledge of substrate-specific bonding protocols essential[6,7]. This review summarises the historical evolution, principles, materials, and current substrate-specific protocols used for bonding to unusual enamel and restorative surfaces.

II. Historical Perspective

Before direct bonding, orthodontic treatment relied on circumferential metal bands, first introduced by Angle in 1907, which were technically demanding, compromised oral hygiene, and were aesthetically unfavourable[8]. Buonocore's 1955 acid-etch discovery, inspired by industrial resin-bonding practice, showed that 85% phosphoric acid applied for 30 seconds dramatically improved resin retention on enamel[1]. Subsequent work by Gwinnett and Matsui, and the etching-pattern classification by Silverstone, clarified that etching removes roughly 10 µm of enamel and creates a porous layer 5–50 µm deep that enhances wettability and resin-tag formation[2].

The synthesis of Bis-GMA resin by Bowen in 1963 provided the chemical basis for modern composite adhesives, offering superior dimensional stability and esthetics compared with earlier acrylics[9]. Newman's 1965 report of epoxy-bonded brackets was the first clinical demonstration that brackets could be attached directly to etched enamel without bands[3]. Over subsequent decades, etching protocols were refined—reducing acid concentration to 30–40% and etching time to 15 seconds—while bracket-base design evolved from smooth pads to mesh, foil, and laser-structured bases to improve mechanical interlock[10]. Parallel advances in dentin bonding, and later in surface conditioning for ceramics, metals, and zirconia, extended bonding capability well beyond sound enamel, setting the stage for contemporary substrate-specific protocols[11].

III. Principles of Orthodontic Adhesion

Orthodontic adhesion is fundamentally micromechanical rather than chemical. Buonocore's original work established that acid-conditioned enamel produces microporosities into which resin penetrates and polymerises to form resin tags[11]. Reynolds later defined the biological and mechanical requirements of a clinically acceptable adhesive, emphasising that bond strength must resist orthodontic and masticatory forces while permitting safe debonding without enamel damage[12]. Meijer further showed that bonding success depends on bracket-base design, adhesive viscosity, and moisture control, and reaffirmed the primarily micromechanical nature of orthodontic adhesion[13,14].

Enamel etching remains the critical determinant of resin-tag formation and bond quality; contamination by saliva or moisture reduces resin penetration and is a leading cause of bond failure[15]. Bond strength is additionally governed by tooth-related, material-related, operator-related, and environmental variables, including adhesive composition, curing protocol, and bracket-base design[16,17]. An ideal orthodontic adhesive should therefore combine sufficient bond strength, ease of manipulation, moisture tolerance, dimensional stability, biocompatibility, and the capacity for atraumatic removal at debonding[12].

IV. Bonding Materials Used in Orthodontics

Composite resin adhesives remain the gold standard for orthodontic bonding because of their superior mechanical properties and predictable clinical performance when appropriate conditioning protocols are followed[12,18]. Glass ionomer cements (GICs) chemically bond to enamel and release fluoride, reducing demineralisation risk, though their bond strength is generally lower than that of composites[19]. Resin-modified glass ionomer cements (RMGICs) combine fluoride release with improved mechanical properties and moisture tolerance, making them valuable in patients at high caries risk[19]. Self-etch adhesives simplify bonding by combining etching and priming into one step, producing a less aggressive etch pattern while achieving clinically acceptable bond strength and reduced technique sensitivity[20]. Universal adhesives, containing multifunctional monomers such as 10-MDP, represent the newest generation of materials capable of bonding to enamel, dentin, and multiple restorative substrates within a single system, although long-term clinical evidence is still accumulating [21,22].

V. Bonding to Unusual Restorative Surfaces

5.1 Composite Restorations. Aged composite restorations lack the oxygen-inhibited layer responsible for chemical bonding, so retention depends on micromechanical roughening using diamond burs, airborne-particle abrasion, or phosphoric-acid etching, followed by a bonding resin[15],[22]. Universal adhesives have produced bond strengths comparable to conventional protocols, sometimes without aggressive roughening, and bonding success correlates with the age and condition of the restoration[15].

5.2 Amalgam Restorations. Because amalgam lacks enamel microstructure, acid etching is ineffective, and mechanical surface modification is essential. Sperber et al. demonstrated that airborne-particle abrasion produced significantly higher shear bond strengths than polished or tarnished surfaces, with the combination of sandblasting and Panavia EX achieving the highest bond strength (18.67 MPa), while surface preparation exerted a greater influence than adhesive choice[23].

5.3 Gold Restorations. Gold alloys are chemically inert with a low-energy surface, requiring both mechanical roughening and metal primers containing 4-META, 10-MDP, or thiophosphate monomers[4]. Ohno et al. showed that creating a porous gold surface through oxidation and acid pickling, combined with a 4-META resin and thiophosphate primer, produced tensile bond strengths of 38 ± 3 MPa compared with 24 ± 2 MPa on conventionally treated flat surfaces, confirming that both mechanical retention and chemical adhesion contribute to durable bonding on noble metals[24].

5.4 Stainless Steel Crowns. Direct bonding to stainless steel crowns, once avoided in favour of banding, is now feasible using airborne-particle abrasion combined with contemporary resin adhesives, which produce clinically acceptable shear bond strengths and reliable retention when isolation and curing are adequate[25,26].

5.5 Ceramic and Porcelain Surfaces. Feldspathic porcelain and glass ceramics, being silica-rich, respond well to hydrofluoric acid etching followed by silane application. A systematic review of 45 in vitro studies concluded that 9.6% hydrofluoric acid etching combined with silane produced the highest bond strengths for silica-based ceramics, while sandblasting with silane was the preferred alternative when hydrofluoric acid was contraindicated[27]. Silane acts as a bifunctional coupling agent, chemically bonding to the ceramic surface while copolymerising with the resin adhesive[28]. Excessive conditioning risks glaze loss or restoration fracture, so the least aggressive effective protocol should be selected[27].

5.6 Zirconia Surfaces. Zirconia is a polycrystalline ceramic lacking a glassy phase, rendering hydrofluoric acid etching ineffective[29]. Airborne-particle abrasion with 30–50 µm aluminium-oxide particles combined with 10-MDP-containing primers is now considered the clinically validated standard, increasing bond strength from approximately 2.5–33 MPa on untreated surfaces to 21.8–57 MPa after conditioning, with durability maintained after thermocycling[30]. Tribochemical silica coating shows promising laboratory results but requires further long-term clinical validation, and excessive abrasion pressure should be avoided to prevent surface defects in highly translucent zirconia[30,31].

VI. Bonding to Altered Enamel Surfaces

6.1 Fluorosed Enamel. Fluorosed enamel has a hyper mineralised, acid-resistant surface overlying a porous subsurface, producing inconsistent etching and frequent bond failure at the enamel-resin interface[32]. In a clinical trial, an adhesion promoter alone—without additional micro abrasion—achieved reliable bracket retention on severely fluorosed teeth after nine months, suggesting that chemical adhesion promoters can simplify bonding on this substrate[33].

6.2 Hypoplastic and Decalcified Enamel. Structural defects in hypoplastic or hypocalcified enamel reduce micromechanical retention. Pretreatment with 5% sodium hypochlorite after phosphoric-acid etching significantly increased shear bond strength in hypocalcified amelogenesis imperfecta by removing residual enamel proteins and improving resin penetration, indicating a role for deproteinization as an adjunct in compromised enamel[34].

6.3 Bleached Enamel. Residual oxygen following bleaching inhibits resin polymerisation and traditionally required a one-week delay before bonding. Application of 10% sodium bicarbonate as an antioxidant for five minutes before bonding permitted immediate adhesive placement with satisfactory one-year clinical performance and no marginal leakage, offering a practical alternative to delayed bonding[35].

VII. Bonding to Dentin and Cementum

Bonding to dentin or cementum becomes necessary in cases of impacted teeth, gingival recession, cervical lesions, or root exposure. Both tissues contain higher organic content and moisture than enamel, with dentin comprising roughly 70% hydroxyapatite, 20% collagen, and 10% water, and cementum containing nearly equal inorganic and organic fractions[36,37]. The collagen network exposed by etching must remain hydrated to prevent collapse, yet excess water inhibits resin infiltration; an acetone wet-bonding technique has been shown to improve dentin wettability, reduce contact angle, enhance monomer penetration, and preserve bond strength after aging by effectively displacing residual water[38]. Cementum bonding is more technique-sensitive because of its thin, irregular, collagen-rich structure, and reliable adhesion depends on meticulous moisture control and gentle conditioning rather than aggressive acid etching[39].

VIII. Surface Preparation Techniques

Surface preparation removes contaminants and weak boundary layers, increases surface energy, and creates retentive features, and its adequacy is one of the strongest determinants of clinical bond durability[40]. Acid etching with 35–37% phosphoric acid remains the standard for enamel and silica-based ceramics but is ineffective on zirconia because of its polycrystalline structure[12,40]. Sandblasting with aluminium-oxide particles is essential for metals, zirconia, ceramics, and aged composites, removing contamination and increasing surface area for micromechanical retention[30,40]. Laser etching using Er:YAG, Er,Cr:YSGG, Nd:YAG, or CO_2 systems can achieve bond strengths comparable to phosphoric-acid etching in selected situations, though clinical outcomes depend heavily on laser parameters, and laser conditioning is generally regarded as an adjunct rather than a full replacement for chemical etching[41,42]. Mechanical roughening with diamond or carbide burs is useful for aged composites and provisional restorations but must be judicious to avoid weakening the substrate[40]. Silane coupling agents remain essential for silica-containing ceramics, forming siloxane bonds with the ceramic surface while copolymerising with resin, whereas silica-poor substrates such as zirconia require phosphate-monomer primers instead[28,30].

IX. Bond Failure and Debonding

Bond failure is multifactorial, influenced by bracket material, tooth location, occlusal loading, operator technique, and patient compliance. In a cohort of 690 brackets, mean survival was approximately three years; polycarbonate brackets failed more than three times as often as metal brackets, and posterior brackets failed roughly five times more often than anterior ones, with the right posterior region carrying the highest hazard ratio (7.7)[43]. These findings are consistent with other reports linking posterior bond failure to greater masticatory load, moisture contamination, and difficulty achieving isolation[44,45]. Prevention relies on an optimum bond strength of about 6–8 MPa, meticulous enamel cleaning and etching, effective moisture control, and careful attention to high-risk sites such as posterior and mandibular teeth[12,43]. Safe debonding requires controlled force application at the bracket-adhesive interface followed by adhesive removal with low-speed carbide burs and water cooling, minimising enamel damage, with polishing to restore surface smoothness thereafter.[43]

X. Recent Advances

Universal adhesives containing 10-MDP can bond to enamel, dentin, ceramics, zirconia, composites, and metals within a single system, simplifying clinical protocols while providing clinically acceptable bond strength, although substrate-specific pretreatment—phosphoric acid for enamel, hydrofluoric acid or sandblasting for ceramics, and roughening for composites—still improves outcomes[46]. Nano-filled composite and glass-ionomer adhesives improve filler loading and reduce polymerisation shrinkage; although a conventional adhesive achieved the highest bond strength in comparative testing, nano-composite and nano-ionomer materials achieved clinically acceptable values, with nano-ionomers additionally offering fluoride release[47]. Laser-assisted bonding, which uses localised laser energy for rapid, low-distortion bonding, has shown promise in materials engineering and may offer future applications for difficult-to-bond restorative surfaces, though clinical orthodontic evidence remains limited[48].

XI. Clinical Implications

As the proportion of adult patients in orthodontic practice increases, clinicians are more often required to bond to restorations and altered enamel rather than sound enamel alone. A substrate-specific approach—phosphoric acid for enamel, hydrofluoric acid and silane for silica-based ceramics, airborne-particle abrasion with MDP primers for zirconia and metals, and mechanical roughening with contemporary adhesives for composites—reduces bracket failure, shortens treatment time, and preserves restoration integrity[5]. Altered enamel surfaces require individualised protocols, such as adhesion promoters for fluorosis and deproteinization for hypoplastic enamel, while emerging materials such as universal adhesives and nano-fillers can simplify clinical workflow when applied with appropriate substrate-specific pretreatment [46,47].

XII. Conclusion

Orthodontic bonding has evolved from Buonocore's acid-etch discovery into a versatile discipline capable of attaching brackets to enamel, restorative materials, and altered dental tissues. While phosphoric-acid etching remains the standard for sound enamel, ceramics, zirconia, metals, composites, and compromised enamel each require substrate-specific conditioning to achieve reliable, durable bonding. Recent innovations, including universal adhesives, nano-filled resins, and laser-assisted techniques, have expanded clinical options and simplified protocols, though further well-designed clinical trials are needed to validate their long-term performance. Ultimately, predictable bonding to unusual surfaces depends on accurate substrate identification, individualised surface conditioning, strict moisture control, and careful clinical execution, allowing clinicians to minimise bracket failure while preserving enamel and restorative integrity throughout orthodontic treatment.

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