

CHAPTER II

LITERATURE REVIEW

Initially, orthodontic brackets or attachments were welded to metal bands. In restorative dentistry, Bounocore,²⁰ in 1955, introduced an enamel acid-etching technique, using 85% phosphoric acid, to increase the retention of acrylic resin to the enamel surface. This technique was adopted in orthodontics for bracket bonding.

Conventional orthodontic adhesive systems utilize three separate steps for bonding brackets to the enamel surface: enamel conditioner, primer and adhesive resin.⁶ Phosphoric acid concentrations of 30% to 40% are most widely used for enamel conditioning and provide the most retentive etching pattern.²¹ After etching, a primer is applied to the enamel, and composite resin is applied to the bracket base. During the final step, the bracket is positioned on the enamel surface and the adhesive is polymerized by a light-curing unit.

Many factors influence bonding procedures. This review is divided into five parts as follows:

2.1 Tooth surface

2.2 Bonding adhesive systems

2.3 Tooth colored materials

2.4 Brackets

2.5 Light curing units (LCUs)

2.1 Tooth surface

2.1.1 The basic bonding mechanism to tooth tissue

The fundamental principle of adhesion to tooth tissue is based upon an exchange process by which the synthetic resin replaces inorganic tooth material.²² This process involves two phases. The first phase is the removal of calcium phosphates to create microporosities in either enamel or dentine. The second phase is a hybridization phase involving infiltration and polymerization of resin within the created microporosities (Figure 1).²² This results in micromechanical interlocking that is the major mechanism of bonding. Another mechanism of bonding is chemical interaction between functional monomers and tooth substrates.²² The bonding mechanism for enamel is different from that for dentin. Dentine is composed of 12% water and 18% organic material by weight, mainly Type I collagen, whereas enamel is composed of 96% hydroxyapatite by weight (Figure 2).²² This particular composition of dentin make bonding to dentin difficult.

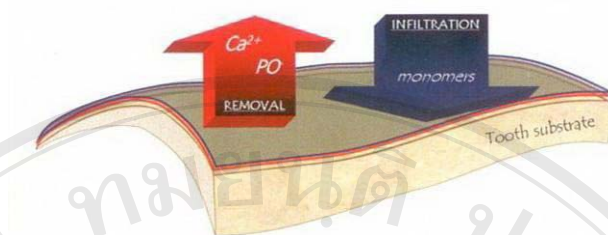


Figure 1 The basic mechanism of adhesion to tooth substrate. (adapted from Van Meerbeek, 2006)

When tooth structure is cut with an instrument, the residual components form a smear layer of debris on the surface and plug the entrance of dentinal tubules. The composition of the smear layer is hydroxyapatite and gel-like denatured collagen.^{23,24}

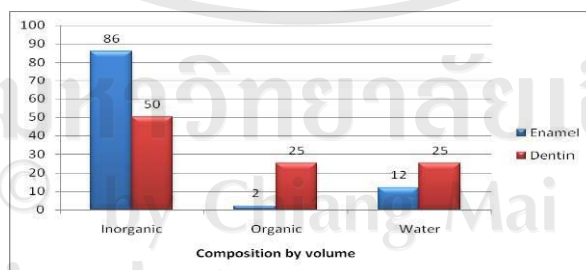
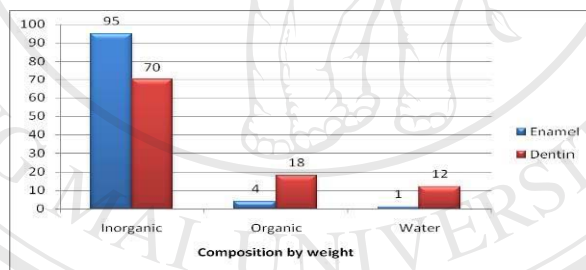


Figure 2 Compositions of enamel and dentin by weight and by volume.

2.1.2 Patterns of etched enamel

Acid etching removes about 10 μm of the enamel surface and creates a microporous layer from 5 to 50 μm deep. The patterns of etched enamel have been classified into three types: Type I is predominantly characterized by the removal of the enamel prism cores, the prism peripheries remaining intact; Type II is predominantly characterized by the removal of the prism peripheries; in Type III there is no prism structure related to enamel morphology (Figure 3).²²

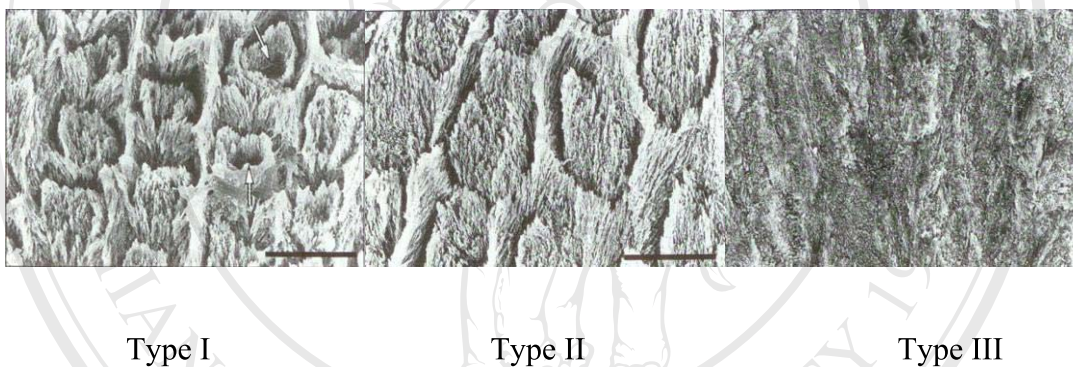


Figure 3 Three patterns of etched enamel (adapted from Van Meerbeek, 2006)

2.1.3 Enamel preparation

The enamel surface needs prophylactic cleaning for proper bond strength. Prophylaxis before acid etching removes organic matrix material, such as acquired pellicles, that can interfere with the bonding process, from the enamel surface.

Some researchers have reported that average shear bond strength values when pumice is used for prophylaxis before bonding were higher than those when prophylaxis was performed without pumice.²⁵ The bond failure rate for self-etching adhesive systems with the omission of pumice prophylaxis before bonding was twice

that for total-etching adhesive systems.²⁶ Pumice prophylaxis prior to enamel surface preparation might be necessary for enamel surface cleansing in order to achieve maximum efficacy of self-etching adhesive systems.

2.2 Bonding adhesive systems

Adhesive systems can be classified based on the adhesion strategy in total-etching and in self-etching adhesive systems (Figure 4).²² The amount of substrate exchange differs among these adhesive systems. The substrate exchange in total-etching adhesive systems is greater than that in self-etching adhesive systems.²⁷

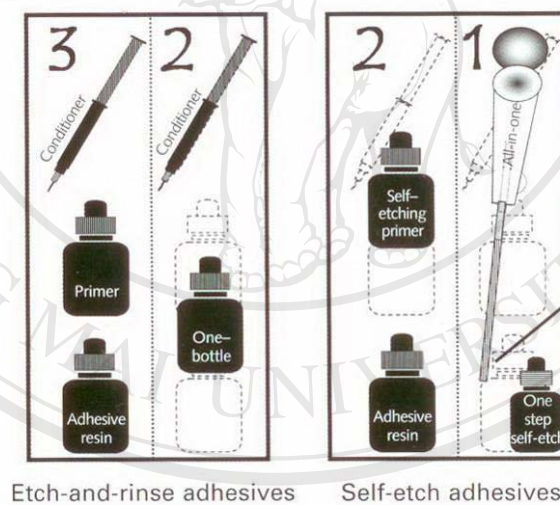


Figure 4 Classification of contemporary adhesives following adhesion strategy and number of clinical application steps (adapted from Van Meerbeek, 2006)

2.2.1 Total-etching adhesive systems

The total-etching adhesive systems include three separate steps: 1) application of the etchant on enamel or dentin, 2) application of the primer with hydrophilic monomer, and 3) application of the bonding or adhesive resin. A simplified, two-step, modification of total-etching adhesive systems combines the applications of both primer and bonding agent into one step. However, the etching step is still separate. The etchant used in the first step is 37% phosphoric acid, and the etching time ranges from 15 to 30 seconds. The etchant dissolves hydroxyapatite crystals, removes the smear layer, creates etched pits, and enhances penetration of resin monomers into etched enamel. Then, the enamel surface is rinsed with water and dried with oil-free air to achieve a chalky enamel appearance. The recommended rinsing time to achieve the most receptive surface for bonding ranges from 5 to 10 seconds, and it should be doubled when using an acid gel.²⁸ A primer is applied on the enamel surface. The liquid acrylic resin is flowed into the microporosities by capillary attraction, and composite resin is then applied and cured. After curing, strong chemical bonds between enamel and acrylic resin are established by polymerization of monomers within the microporosities, and by copolymerization of remaining carbon-carbon double bonds with the matrix phase of the resin composite.²² The two types of resin tags within the etch-pits are 1) macro-tags that fill the space surrounding the enamel prisms, and 2) micro-tags that fill the etch-pits at the etched enamel prism cores (Figure 5).²⁷ The greater the quantity of micro-tags, the higher the bond strength.

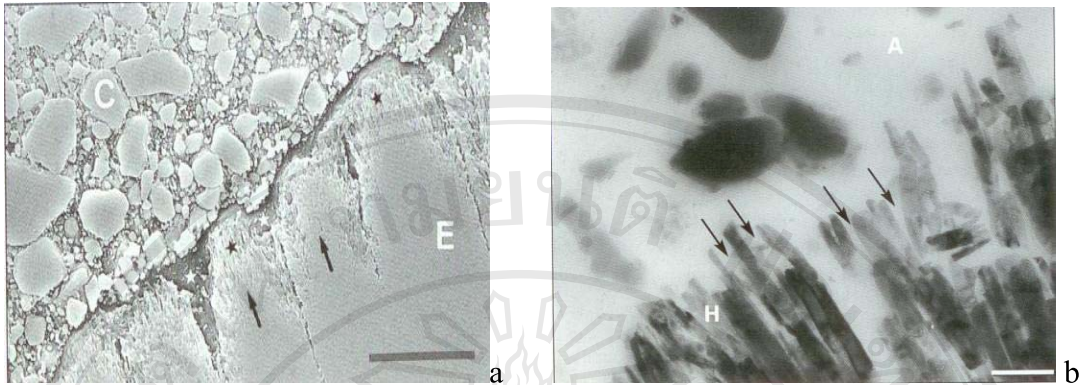


Figure 5 a, b Field-emission scanning electron microscopy (Fe-SEM) photomicrograph (a) and transmission electron microscopy (TEM) photomicrograph (b) show a micro-mechanical interlocking of the resin-enamel (E) interface when using total-etching. Macrotags (white stars) are formed circularly between enamel prism (black arrows) peripheries. Microtags (black stars) envelope hydroxyapatite crystals at the enamel prism cores. C = luting composite; A = adhesive resin; H = hydroxyapatite (adapted from Van Meerbeek, 2006)

In dentin, the phosphoric acid etching uncovers networks of collagen and removes calcium phosphate and the smear layer. As a result, the primary bonding mechanism of total-etching adhesive systems is hybridization or infiltration of resin within the exposed collagen fibril.²² This infiltration results in a hybrid tissue, composed of collagen, residual hydroxyapatite, resin, and traces of water, known as the hybrid layer. However, total-etching adhesive systems are technique-sensitive in the priming step. In acetone-based adhesives, a wet-bonding technique is used, whereas, in water/ethanol based adhesives, a dry-bonding technique is used.²⁷

Complete removal of the etchant and dissolved calcium phosphate and preservation of the clean etched enamel without contamination are important to the

longevity of the resin-enamel bond. For this reason, the use of total-etching adhesive systems is difficult and technique-sensitive. Moreover, the total-etching adhesive systems entail some problems, including time consumption, inconvenience for patient and operator, decalcification, development of white spot lesions around bonded orthodontic appliances, and the possibility of damaged enamel surfaces during debonding and removal of residual resin.²⁹⁻³³

A simplification of a three-step total-etching adhesive system is the combination of the primer and the adhesive resin, resulting in a two-step total-etching adhesive system. It has been reported that three-step total-etching adhesive systems have high potency and longevity of bonding integrity compared to two-step total-etching adhesive systems.²²

2.2.2 Self-etching adhesive systems

Self-etching adhesive systems have been developed in operative dentistry by combining both etchant and priming agents into a single acidic primer solution.

Self-etching adhesive systems were initially used on dentin. They have subsequently been found to be effective also on enamel. The advantages of these self-etching adhesive systems are reduction of errors during application and manipulation, omitting the step of rinsing the etchant from the tooth surface, and saving chair-side time.³⁴ The simplified procedures of self-etching adhesive systems may also reduce technical errors occurring in the use of total-etching adhesive systems, such as over-etching, over-wetting, or over-drying of the prepared tooth surface.³⁵

Three mechanisms of self-etching adhesive systems act to stop the etching process. Firstly, phosphoric acid and methacrylate groups are combined into a compound which dissolves calcium from hydroxyapatite crystals. The dissolved calcium combines with phosphate groups. The resulting calcium phosphate complex causes enamel demineralization, resulting in a shallow depth of etching pattern. The high concentration of calcium phosphate complex impedes further dissolution of the apatite. So, the depth of enamel demineralization is limited.³⁶ Secondly, the air blowing step causes an evaporation of the solvent in the primer. The viscosity of the primer is increased. Simultaneously, the acid groups are slowly transported into the enamel prisms. Finally, the primer is light-cured, the monomers are polymerized and the transport of acid groups to the interface is stopped. The self-etching adhesive systems leave a residual smear layer within the bonding resin or the interfacial structure. Residual solvent weakens the bond integrity and provides channels for nanoleakage.²² However, residual solvent does not affect bond strength. It is advantageous that the depth of demineralization is equal to the depth of penetration of the primer.³⁷ The degree of penetration of self-etching adhesive systems is less than that of total-etching adhesive systems.

Some studies suggest that the microporosities after the acid etching process might permit penetration of small resin tags into the enamel surface (Figure 6). As a result, microscopic mechanical interlocks between enamel and resin are created. The self-etching adhesive systems permit resin infiltration into enamel to a depth of 0.6 to 0.7 μm . Phosphoric acid etching allows slightly deeper infiltration of resin tags (1 μm -long) into the enamel surface in order to produce enamel hybrid layers. However,

this superficial resin penetration of self-etching adhesive systems provides sufficient resin-enamel bond strength.³⁵ The greater the penetration by the adhesive, the greater the risk of enamel damage on de-bonding.^{38,39}

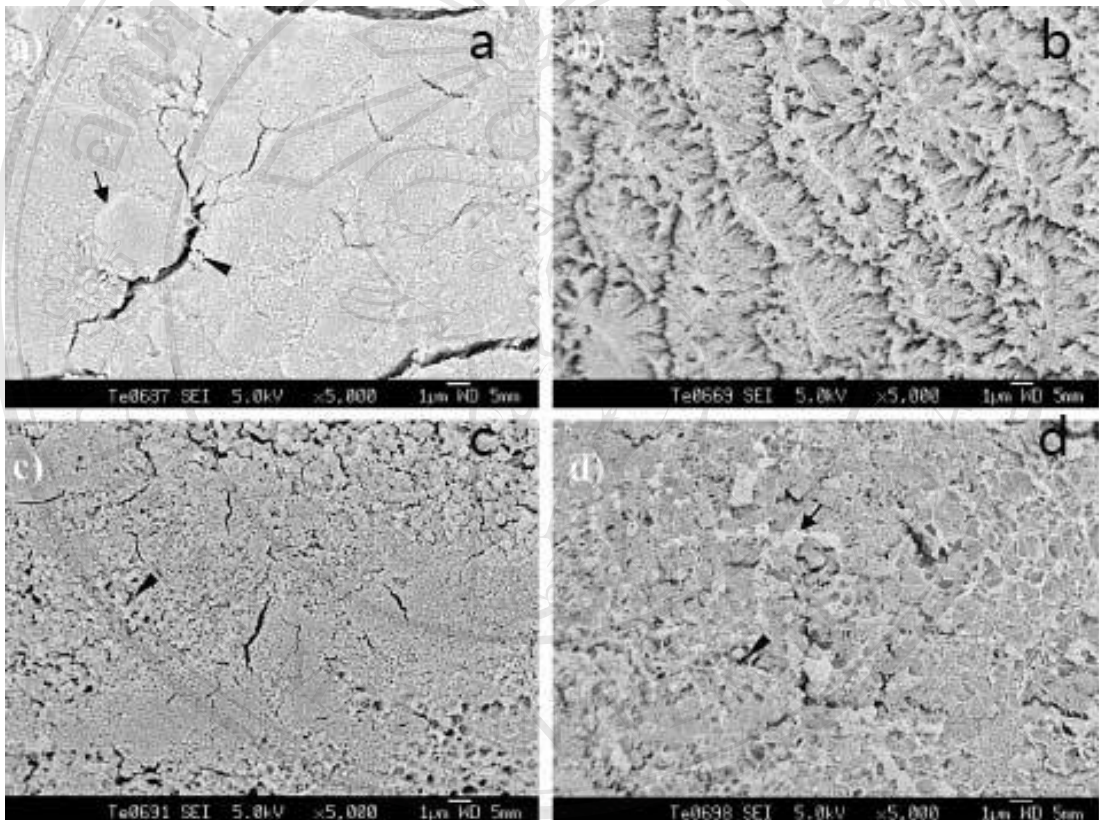


Figure 6 Field-emission scanning electron microscope (FE-SEM) pictures of enamel surfaces. (a) Cleaned surface: circles are enamel rods (arrow), and small holes (arrowhead) are observed. (b) Phosphoric acid etched surface: highly roughened enamel surfaces and enamel rods are evident. (c) Polyacrylic acid etched surface: number and size of holes (arrowhead) are increased compared with cleaned surface. (d) Megabond self-etching primed surface: residual organic pellicles are present (arrow), and holes are also identified (arrowhead). (adapted from Yamada, 2002)

The self-etching adhesive systems contain aqueous mixtures of acidic functional monomers, phosphoric acid in carboxylic acid esters and other constituents. These systems can be classified into two-step or one-step application procedures, or by etching aggressiveness. The first self-etching adhesive system was developed as a two-step self-etching adhesive system with two separate applications: etchant and bonding resin. Recently, manufacturers have attempted to combine etchant, primer and bonding resin into a single solution (all-in-one adhesives), rendering the systems one-step self-etching adhesive systems.²⁴

The etching aggressiveness of self-etching adhesive systems can be classified into “strong,” “intermediary,” and “mild” adhesive systems (Figure 7). The “strong” self-etching adhesive systems have a pH of 1.0 or lower, which results in deep demineralization effects.⁴⁰ At the enamel surface, this high acidity produces an acid-etch pattern the same as that of total-etching adhesive systems.⁴¹ In dentin, collagen and almost all of the hydroxyapatite are dissolved. It is difficult to remove residual solvent within the adhesive interface of the “strong” self-etching adhesive systems due to high acidity. So, the bond strength of the “strong” self-etching adhesive systems are low, especially in dentin.⁴² The long-term durability of these “strong” self-etching adhesive systems should be further investigated.

The “mild” self-etching adhesive systems have a pH of 2.0, and cause shallow, partial demineralization, less than one micrometer, in dentin. The thickness of the hybrid layer with the “mild” self-etching adhesive systems is much thinner than that with the “strong” self-etching adhesive systems or the total-etching adhesive systems.⁴⁰ This superficial demineralization is incomplete, leaving residual

hydroxyapatite remaining attached to collagen.²² The calcium in the residual hydroxyapatite within the hybrid layer forms additional chemical bonding with functional monomers. Chemical bonding with functional monomers may prevent marginal leakage.

The “intermediary” self-etching adhesive systems have a pH of 1.5. The two-fold build-up of the dentinal hybrid layer produces a completely demineralized superficial layer and a partially demineralized base layer.²⁷ These adhesives are more acidic than those in the “mild” self-etching adhesive systems, and better micromechanical interlocking is achieved with enamel and dentin surfaces. The residual hydroxyapatite at the hybrid layer base still has chemical intermolecular interaction.²⁷



Figure 7 The interaction of different etching aggressiveness of self-etching adhesive systems with dentin. (Left) Unaffected dentin is covered by a smear layer. (Right) Interaction of three self-etch adhesive systems with dentin and the smear layer. The potency of smear layer removal increases from mild, intermediary and strong respectively. (adapted from Van Meerbeek, 2006)

Unlike bonding to sound dentin, the application of self-etching adhesive systems to enamel is controversial. Bishara *et al.*⁴³ reported that bonding with self-etching adhesive systems to ground enamel was inferior when compared to that with total-etching adhesive systems. On the other hand, other studies have shown that self-etching adhesive systems might be used as alternatives to total-etching adhesive systems for ground enamel.⁴⁴ Kanemura *et al.*⁴⁵ reported that self-etching adhesive systems produced good adhesion to ground enamel. However, shallow etching patterns produced low bond strength to intact and unground enamel. Perdigao *et al.*⁴⁶ showed that there was no correlation between the less well defined enamel etching pattern produced by self-etching adhesive systems and their shear bond strength to ground enamel.

Bishara *et al.*^{43,47} reported the effectiveness of a self-etching adhesive system for bonding orthodontic brackets with composite resin adhesives. The self-etching primers composing phenyl-P provided clinically acceptable shear bond strength when used with highly filled composite adhesive (Panavia 21, J.C. Morita, Kuraray, Japan), but did not give sufficient shear bond strength when used with lightly-filled composite adhesive (Clearfil Liner Bond 2, J.C. Morita) or traditional composite resin adhesive.

2.2.3 Total-etching and self-etching adhesive systems

There is controversy regarding the use of self-etching adhesive systems. The shear bond strength values for brackets bonded using a self-etching adhesive system were significantly lower than for those bonded using a total-etching adhesive system.⁸ However, many researchers reported no significant difference.^{3,4,6,36-38,48} Attar *et al.*¹¹

reported that the shear bond strength of orthodontic brackets bonded by using one-step, two-step self-etching or total-etching adhesive systems were not statistically significantly different. However, a significant decrease in shear bond strength was discovered when self-etching primer was not air-thinned or air-dispersed as recommended by manufacturer's directions.³⁷

Some studies have suggested bond strength values ranging from 2.8 to 10.0 MPa as being adequate for clinical use.^{20,49,50} Most clinical orthodontic bonding requires a shear bond strength of 6.0 to 8.0 MPa.⁵¹ Retief *et al.*⁵² demonstrated that maximum bond strength of an orthodontic bracket should be less than the breaking strength of enamel, which is about 14 MPa, but this was an *in-vitro* value in ideal substrate conditions and would probably be less in *in-vivo* conditions.

Several articles have reported similar bond failure rates between total-etching adhesive system-bonded brackets and self-etching adhesive system-bonded brackets.^{3,18,48,53} When tested under contaminated conditions, self-etching adhesive systems have also produced clinically acceptable bond strength and performed better than total-etching adhesive systems.^{10,48,54} The mean shear bond strength values, obtained by different orthodontists who used self-etching adhesive systems, were not significantly different, and these findings support the notion that self-etching adhesive systems are less technique-sensitive than total-etching adhesive systems.⁵⁵

Alijoubouri *et al.*⁷ compared the mean bonding time of light-cured composite using conventional etching and self-etching adhesive systems. They found that the bonding time with the self-etching adhesive system was significantly reduced by 1.97 seconds/tooth in comparison to the conventional etching adhesive system.

2.2.4 Two-step and one-step self-etching adhesive systems

The main components of one-step self-etching adhesive systems are acidic monomers like 4-Methacryloxyethyl trimellitic acid, 10-Methacryloyloxy decyl dihydrogen phosphate, and 2-Methacryloxy ethyl phenyl hydrogen phosphate. These components are similar to those of two-step self-etching adhesive systems. One-step self-etching adhesive systems provide relatively low bond strength values in comparison to those provided by two-step self-etching adhesive systems and total-etching adhesive systems. Due to high hydrophilicity, water is absorbed through the adhesive layer, which acts as a permeable membrane.^{42,56} Additionally, phase separation has been found in the self-etching adhesive systems, which consist of the mixture of hydrophobic and hydrophilic components. The solvents in adhesive systems gradually evaporate, so water is separated from the other adhesives. Droplets from this effect may contribute to bond degradation, and the remaining water in the adhesive layer may also affect bond strength.²² However, one-step self-etching adhesive systems reduce the chance of saliva contamination, save chair-side time and have several advantages.³⁴

Representative two-step self-etching adhesive systems include AdheSE (Ivoclar, Vivadent, AG, Liechtenstein), Clearfil SE Bond (Kuraray), Clearfil Protect Bond (Kuraray), Optibond Solo Plus Self-etch (Ormco, Orange, CA), and Tyrian SPE One-Step Plus (Bisco, Schaumburg, IL).

Representative one-step self-etching adhesive systems include Clearfil S³ Bond (Kuraray), G-Bond (GC, America), i-Bond (Heraeus Kulzer, LLC) and Xeno IV (Dentsply, Caulk).

Clearfil S³ Bond, a one-step self-etching adhesive successor of Clearfil SE Bond (Table 1), a two-step self-etching adhesive based on 10-methacryloyloxy decyl dihydrogen phosphate, shows lower dentin bond strength than its predecessor. The pH level of Clearfil S³ Bond is less acidic than that of Clearfil SE Bond (2.4 versus 1.8, respectively). The bond strength of Clearfil S³ Bond on unground enamel is statistically similar to that of a more aggressive self-etching adhesive, such as Adper Prompt L-Pop (3M ESPE, US).²⁴ The manufacturer of Clearfil S³ Bond has reported that the difference between the two 10-methacryloyloxy decyl dihydrogen phosphate-based adhesives might lie on the “molecular dispersion technology” that maintains the homogeneity of Clearfil S³ Bond and prevents phase separation that occurs with acetone-based one-step self-etching adhesive systems.⁴² Moreover, a recent study reported that Clearfil S³ Bond was more resistant to mechanical stress than Clearfil SE bond.⁵⁷ Some studies have demonstrated that both Clearfil adhesives provide good resistance to clinical fatigue of adhesives containing 10-methacryloyloxy decyl dihydrogen phosphate.^{58,59}

Table 1 Compositions of Transbond XT™, Clearfil SE Bond and Clearfil S³ Bond

Adhesives	Composition	Type
Etchant (Ormco, USA) and Transbond XT™ (3M Unitek, Monrovia CA, USA)	Etching gel : 37% Phosphoric acid Primer : TEGDMA, Bis-GMA Paste : Bis-GMA, TEGDMA, silane-treated quartz, amorphous silica, camphorquinone	Total-etching
Clearfil SE Bond (Kuraray, Japan)	Primer: 10-MDP, HEMA, hydrophilic DMA, tertiary amine, water, photo-initiator Bonding: 10-MDP, HEMA, bis-GMA, hydrophilic DMA, tertiary amine, silanated, colloidal silica, photo-initiator (Filler : Silicate colloidal Solvent : no, pH = 1.8)	Two-step self-etching
Clearfil S ³ Bond (Kuraray, Japan)	10-MDP, HEMA, bis-GMA, water, ethanol, silanated colloidal silica, camphorquinone (Filler : Colloidal silica, Solvent : Ethyl alcohol, pH= 1)	One-step self-etching

Abbreviations: bis-GMA, bisphenol glycidyl methacrylate; DMA, dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; 10-MDP, 10-methacryloyloxy decyl dihydrogenphosphate

The total-etching adhesive and two-step and one-step self-etching adhesive systems have several advantages and disadvantages.

Total-etching adhesive systems²²

Three-step total-etching adhesive systems

Advantages

- Separate application of conditioner, primer, and adhesive resin
- Low technique sensitivity
- Proven effectiveness of adhesion to enamel and dentin *in vitro* and *in vivo*
most effective and consistent results
- Best long-term results
- Possibility for particle-filled adhesive (“shock absorber”)

Disadvantages

- Risk of over-etching dentin (highly concentrated phosphoric-acid etchants),
resulting in incomplete resin infiltration
- Time-consuming three-step application procedure
- Post-conditioning rinsing required (risk of surface contamination)
- Sensitive to overwet or overdry dentin surface conditions (collagen collapse)
- Weak resin-collagen interaction (which may lead to nanoleakage)
- Elaborate application procedure

Two-step total-etching adhesive systems

Advantages

- Basic features of three-step systems
- Simpler application procedure
- Possibility for single-dose packaging
- Consistent and stable composition
- Controlled solvent evaporation (when provided in single-dose packaging)
- Hygienic application (to prevent cross contamination)
- Possibility for particle-filled adhesive (“shock absorber”)

Disadvantages

- Application procedure not substantially faster (multiple layer)
- More technique-sensitive (multiple layers)
- Risk of a bonding layer that is too thin (no glossy film, no stress relieving “shock absorber” insufficiently polymerizable due to oxygen inhibition)
- Effects of total-etching technique
- Risk of over-etching
- Post-conditioning rinse phase required
- Sensitive to dentin wetness
- Weak resin-collagen interaction
- Collagen collapse

- Lower bonding effectiveness than for three-step total-etching adhesives in long-term studies.

Self-etching adhesive systems²²

Two-step self-etching adhesive systems

Advantages

- No etching, post-conditioning rinsing, or drying (which may be difficult to standardize)
- Time-saving application procedure
- Simultaneous demineralization and resin infiltration
- Less sensitivity to diverse dentin-wetness conditions
- Possibility for single-dose packaging
- Consistent and stable composition
- Controlled solvent evaporation (when provided in single-dose packaging)
- Hygienic application (unidose, to prevent cross contamination)
- Possibility for particle-filled adhesive (“shock absorb”)
- Effective dentin desensitizer
- Separate adhesive resin (as compared to one-step adhesives)
 - Better mechanical strengths
 - No complex mixtures of hydrophobic and hydrophilic components
- Good performance *in vitro* and *in vivo*, approaching bonding effectiveness of etch- and- rinse adhesives, in particular “mild” two-step self-etch adhesives
- Reported reduced postoperative sensitivity
- Excellent three-year clinical performance for mild two-step self-etch adhesives

Disadvantages

- More elaborate application procedure than one-step solutions
- Incompatibility with autocuring composites (in particular low-pH self-etch adhesives)
- More long-term clinical research required
- Most self-etch systems contain water, which influences polymerization adversely
- Reduced shelf life (hydrolysis of monomers)
- Conflicting results in literature concerning bonding effectiveness to enamel, in particular for mild self-etch adhesives
- Bonding effectiveness very dependent on composition of adhesive solution
- High hydrophilicity (due to acidic monomers)
- Promotes water sorption
- Impaired durability

One-step self-etching adhesive systems

Advantages

- Most time-efficient application procedure
- No etching, post-conditioning rinsing, or drying (which may be difficult to standardize)
- Simultaneous demineralization and resin infiltration
- Less sensitivity to diverse dentin-wetness conditions
- Possibility for single-dose packaging

- Consistent and stable composition
- Hygienic application (unidose, to prevent cross contamination)
- Possibility for particle-filled adhesive (“shock absorb”)
- Possibility that phase separation in combination with strong air-blow may help to remove majority of water in adhesive

Disadvantages

- Complex mixes of hydrophobic and hydrophilic components, together with water and high concentrations of solvents
- Prone to phase separation and entrapment of droplets in adhesive layer (when not containing sufficient 2-hydroxyethyl methacrylate)
- More technique-sensitive
- No long-term clinical evaluation
- Less sealing capacity; acts as a semipermeable membrane
- Most self-etch systems contain water, which influences polymerization adversely
- Reduced shelf life (hydrolysis of monomers)
- High hydrophilicity (due to acidic monomers)
- Promotes water sorption
- Impaired durability
- Incompatibility with autocuring composites
- Insufficient long-term clinical research
- Conflicting results in literature concerning bonding effectiveness to enamel for mild self-etch adhesives

2.3 Tooth colored materials

There are several types of tooth-colored adhesives such as glass ionomer, resin composite, resin modified glass-ionomer, polyacid modified resin composites, compomer and giomer. However, resin composite is the most effective and consistent adhesive available for orthodontic bonding.⁶⁰ Transbond XT™ (3M Unitek, US) resin composite, which is a highly-filled adhesive, contains 14% Bisphenol glycidyl methacrylate, 9% 2,2-bis(4-(2-Methacryloxyethoxy) phenylpropane, 77% quartz glass and submicron silica glass, and presents higher bond strength values than other adhesives do.¹⁵

The Adhesive Precoated system (APC, 3M Unitek Dental Products, Monrovia Cal., USA) is a system in which adhesive material is precoated at the bracket base by the manufacturer. It provides a uniform adhesive thickness, reduces the number of bonding procedures, enhances the quality of the adhesive system, saves chair side-time and permits easier bonding procedures. The adhesive in the APC system is an improved and modified version of Transbond XT™ adhesive, improved by increasing polymer viscosity. The difference between the adhesives used on precoated brackets and uncoated brackets is in the percentages of the ingredients in the material, even though there is no difference in the chemical composition of the adhesives (Table 2). The APC has a great amount of filler (80%).⁵¹

The APC II system is a development of the APC system.⁶¹ This system has the same components as Transbond XT™. However, the consistency of the APC II is lower than that of the APC system. It is easy for the operator to place and press the

bracket on the tooth surface. Recently, the APC Plus system has been introduced.⁶² This system has hydrophilic monomers and an acid oligomer (a carboxylated methacrylate), and this improves tolerance to humidity compared to the initial products. This system contains a small amount of bisphenol glycidyl methacrylate to enhance handling characteristics, package stability and fluoride release. Moreover, its pink color is changed to white when exposed to light, ambient or curing. However, changing of color is not an indication of polymerization; it is intended to facilitate clean-up of adhesive remnant after de-bonding.⁶²

Table 2 Compositions of Transbond XT™, APCII and APC

Adhesive/ Materials	Transbond XT™ and APCII	APC
Resin		
Bisphenol glycidyl methacrylate	14%	12%
2,2-bis(4-(2Methacryloxyethoxy)phenyl)propane	9%	8%
Fillers	77%	80%
Silylated quartz		
Silylated filler and submicron silica		
Curatives	<1%	<1%
Camphorquinone		
Others	<1%	<1%

Cooper *et al.*¹⁹ compared the advantages of the APC system and those of conventional light-cured adhesive systems. The APC system offers consistent quality and quantity of light-cured adhesive, easier clean-up after bonding, reducible waste, better asepsis, and supply control. Few studies have compared the shear bond strength of precoated and uncoated brackets. The conclusions from comparisons of shear bond strength of precoated and uncoated brackets are controversial. Some researchers have claimed that there is no significant difference in shear bond strength between precoated and uncoated brackets.^{1,63}

2.4 Ceramic brackets

Ceramic brackets were introduced in 1986.⁶⁴ They are made of either monocrystalline or polycrystalline sapphire. They are more esthetic than metal, coated metal or plastic brackets.¹⁷ Ceramic brackets have higher strength, adequate force control during long treatment times, resistance to wear and deformation, and minimal discoloration.⁶⁵

2.4.1 There are three types of ceramic brackets.⁶⁴

2.4.1.1. Monocrystalline brackets are fabricated by heating aluminium oxide at temperatures higher than 2100 °C followed by slow cooling. The monocrystalline brackets are more optically transparent than polycrystalline brackets.⁶⁶

2.4.1.2 Polycrystalline brackets are fabricated by blending aluminium oxide particles using binding and sintering processes at temperatures higher than 1800 °C. The heat treatment removes artifacts and relieves stress. Polycrystalline ceramics are translucent because they contain large ceramic grains. However, the material tends

weaken as the grain size exceeds 30 microns. Heat treatments after production must be controlled to prevent grain fusion. The main advantage of polycrystalline brackets is the ability to mold brackets, although, a disadvantage of the molding process is that there are defects at grain boundaries that are initial points for crack propagation under stress.

2.4.1.3 Zirconia brackets are made of stabilized zirconium which are strong and have low friction. They are cheaper than monocrystalline ceramic brackets. However, zirconia brackets have problems of color and opacity, making them less aesthetic.⁶⁵

2.4.2 Properties of ceramic brackets⁶⁴

1. Biocompatibility. Ceramic brackets are stable in the oral environment, and are biocompatible with oral tissues, whereas metal brackets are composed of Nickel and Chromium. Nickel dust is potentially carcinogenic in nasal and lung tissues and can produce allergic reactions in mucous membranes. Chromium causes lung cancer (at industrial exposure levels) and chronic dermatitis.

2. Hardness. Ceramic brackets, contain aluminium oxide, have significantly higher (about nine times) hardness than stainless steel and enamel.⁶⁷

3. Tensile strength. The tensile strength of monocrystalline alumina is higher than that of the following, in decreasing order of their hardness: polycrystalline alumina, ceramic-filled plastic and stainless steel.¹⁷

4. Fracture toughness. Fracture toughness of ceramics is 20-40 times less than that of stainless steel, and this low toughness may lead to uncontrolled bracket wing failure during function and to problems during de-bonding.⁶⁷

5. Frictional resistance. Frictional resistance of ceramic brackets is high. Placing metal-lined arch wire slots in new ceramic brackets can reduce these problems.⁶⁶ Polycrystalline ceramics have higher friction than monocrystalline ceramics and metal brackets due to their rougher surface.⁶⁵

6. Bond strength. Ceramic brackets can be bonded to adhesives by either chemical or mechanical bonds or both. The shear bond strength of ceramic brackets is high, so enamel fracture during function and de-bonding may be significant problems.⁶⁸ Though the same adhesive is utilized, the monocrystalline brackets produce a higher shear bond strength than polycrystalline brackets and stainless steel brackets do. Comparative bond strength studies of ceramic and metal brackets show large variations according to bond strength measurement tests. Some studies reported no statistically significant difference in mean shear bond strength values among chemically, mechanically retained ceramic brackets and metal brackets.^{52,69,70}

However, some studies reported that brackets with chemical retention showed significantly higher shear bond strength than those with mechanical retention.⁷¹⁻⁷⁵

Bond strength can be modified by different adhesives, different enamel conditioning⁷² and different etching time.⁷⁶

6.1 Chemical bonding. Chemical bonding to ceramic surfaces is achieved by silanization with bifunctional coupling agents. A silane group at one end of the

coupling agent chemically bonds to hydrolyzed silicon dioxide at the ceramic surface, and the other end to the adhesive resin (Figure 8). This chemical bonding of ceramic brackets permits greater strength over the adhesive interface. However, the high shear bond strength is disadvantageous because enamel fracture is more likely to be found after de-bonding than with mechanical bonding.

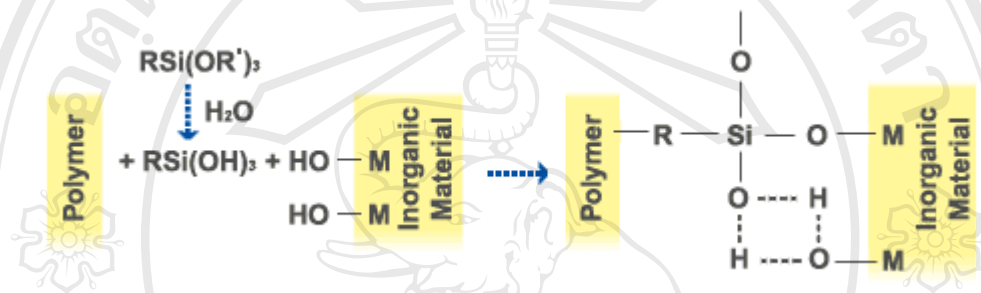


Figure 8 The coupling mechanism of ceramics (from www.google.com)

6.2 Mechanical bonding. Ceramic bracket bases are generally etched with hydrofluoric acid and ammonium bifluoride to increase surface area, and to create microporosities. The adhesive resin flows into the microporosities, forming micromechanical bonds. Manufacturers have designed brackets with bases that have various retentive designs, such as serrated, retentive grooves, mechanical spheres, dovetails, chemo/mechanical dimples, silane-coated buttons and polymeric bases.⁶⁵

In conclusion, mechanically-retained brackets have adequate bond strength and cause less enamel damage during de-bonding than chemically retained brackets do. If the bond strength is high, the bond failure rate is higher at the enamel-adhesive interface than that at the bracket-adhesive interface and the high bond strength induces enamel fractures.¹⁵ The high bond strength of ceramic brackets results from

either (1) silanization of the bracket base, or (2) mechanical retention, or (3) a combination of both (1) and (2).

7. Re-bonding ceramic brackets. The bond strength of recycled brackets is 30% less than that of new ceramic brackets,⁶⁴ but clinically adequate bond strength is maintained and recycled brackets show few enamel fractures on de-bonding.

8. De-bonding ceramic brackets. It is difficult to remove ceramic brackets due to their rigidity and brittleness. After de-bonding ceramic brackets, a higher incidence of enamel fracture has been found than after de-bonding metal brackets. De-bonding ceramic brackets might leave residual ceramic on the tooth surface. Using a high-speed handpiece with a diamond bur to remove residual ceramic is both difficult and time consuming. However, using a low-speed procedure generates heat and irritates pulpal tissues. Additionally, skin and eye irritation may occur in patients and operators from contact with ceramic dust. There are several methods to de-bond ceramic brackets, such as conventional de-bonding pliers, Howe pliers, Weingarts pliers, ligature cutters, ceramic-bracket-specific de-bonding pliers, electrothermal equipment, ultrasonic scalers, laser-aided de-bonding techniques and de-bonding agents.⁶⁵

Current ceramic brackets (3M Unitek) have a de-bonding slot and stress concentrator located on the base of their Clarity™ brackets (polycrystalline with metal-reinforced slot) which are as easy and safe for de-bonding as metal brackets. The design of the bracket comprises a metal-lined archwire slot to decrease friction between the archwire and the ceramic surface, and also a de-bonding slot on the base.

The de-bonding slot collapses under gentle pressure from Howe or Weingart pliers.⁶⁵ The amount of residual adhesive remaining on the enamel surface after de-bonding ceramic brackets is similar to that after de-bonding metal brackets.⁴³ Failure of the bond at the bracket/adhesive interface decreases the probability of enamel damage, but necessitates the removal of more residual adhesive after de-bonding. The recommended de-bonding methods should follow the individual manufacturers' guidelines.

Adhesive Precoated brackets, both metal and ceramic, were introduced in 1992. They are brackets that have been precoated with adhesive material at the bracket base.

There are controversies regarding shear bond strength between uncoated and precoated brackets. Bishara *et al.*⁵¹ in 1997, reported that precoated metal brackets had significantly lower shear bond strength than uncoated metal brackets, but that precoated ceramic brackets using the modified resin composite had similar shear bond strength to those using the uncoated ceramic brackets. However, Bishara *et al.*¹⁸ in 2005, reported that shear bond strength of precoated metal and ceramic brackets were significantly greater than those of uncoated metal and ceramic brackets.

2.5 Light curing unit (LCU)

There are five types of light curing unit used in clinical practice.⁷⁷

2.5.1 Quartz-Tungsten-Halogen curing unit. A halogen lamp produces light whose wavelength peaks at 400 to 500 nm. Energy is given off as heat, which can damage teeth and which must be controlled.⁷⁸ Thus, the curing lamps need calibration to reduce the heat that is radiated from the light tip.

2.5.2 Plasma Arc Curing (PAC) Unit. A plasma arc curing unit is a high intensity visible light-curing unit. It produces a wide wavelength of light covering 380 to 500 nm, and a power density up to 2500 mW/cm². However, the Argon bulbs have a short shelf life. Several dental manufacturers recommend that these lamps should not be used for curing because of poor curing outcomes.

2.5.3 Laser. Laser light produces wavelength of light about 480 nm for initiating camphoroquinone. Laser light produces less heat than other light-curing units, because of limited infrared output. However, a major disadvantage of laser light is a narrow light guide. So the clinician has to overlap curing cycles in large restorations.

2.5.4 Metal Halide Curing Unit. A metal halide curing unit is a high intensity curing unit. Electricity passes through a tungsten wire in an arc tube and produces the light. A disadvantage of this curing unit is less efficiency for polymerization in deep areas.

2.5.5 Light-Emitting Diode (LED). A light-emitting diode is a semiconductor that emits a narrow wavelength of light, about 470 nm. A light-emitting diode offers many advantages over other curing lamps. A light-emitting diode is a low energy consumption device, allowing it to be used for up to 10,000 hours. Furthermore, the thermal emission of a light-emitting diode is significantly lower than that of a conventional halogen lamp.⁷⁸