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REVIEW ARTICLE

Adhesion concepts and techniques for laboratory-processed indirect dental restorations

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Abstract The purpose of this review was to analyze the existing literature on surface conditioning of the veneering surface of substructure restorative materials in dental laboratories. New technologies are constantly improving the treatment options for fabricating dental restorations, and new materials and adhesion procedures are being offered to clinicians and dental technologists. To establish a reliable adhesion between the veneer and substructure in the dental laboratory, various surface treatment procedures and adhesion promoters are employed. The composition of a material influences the adhesion approach selected, and implementing a reliable adhesion strategy is critical for the predictability of veneered indirect dental restorations. However, surface treatment of a wide range of available material options can be challenging. Therefore, understanding various adhesion processes for different restorative materials may assist dental technologists in selecting the best and appropriate surface conditioning protocol for each dental restorative material category.

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1. Introduction

Optimal tooth preparation and prosthesis design, proper materials, reliable adhesion, physiologically acceptable soft tissue treatment, acceptable occlusion, and clear communication between the patient, dentist, and dental technologists are essential for the long-term success of dental restorations (Tipton, 2001). Adhesion techniques are well practiced in dentistry at different levels, from dealing with adhesive materials on natural teeth in clinics to creating a bond between different materials to fabricate indirect restorations in dental laboratories. Enamel and dentin etching with phosphoric acid, initially introduced by Buonocore in the 1950 s, is one of the most important innovations that has revolutionized adhesive dentistry (Buonocore, 1955).

Most cases in clinics are related to bonding direct restorative materials to enamel or dentin, with the latter being the preferred choice owing to better adhesion (Sofan et al., 2017). However, adhesion concepts in dental laboratories vary significantly from those in the clinical environment. This is mainly due to the different chemical structures of biomaterials processed in dental laboratories, which necessitate different surface treatments (Terry and Blatz, 2011). Furthermore, different restorative dental materials with different compositions are continuously being introduced by several manufacturers. Therefore, understanding the available adhesion concepts for different materials in dental laboratories and employing a suitable adhesion technique are vital for the success of dental restorations. The most common surface treatments reported in the literature are grit blasting, pyrochemical silica coating, tribochemical silica coating, and chemical treatments using acids and bases (Matinlinna et al., 2018; Saade et al., 2019). Most studies on adhesion concepts in the literature have focused on clinical situations, and information regarding the same in dental laboratories is scarce.

The purpose of this review was to analyze the existing literature on the surface conditioning of veneering surfaces of indirect restorative materials in dental laboratories, which could benefit dental technologists in selecting the best and appropriate surface conditioning protocol for each dental restorative material category.

All original peer-reviewed in-vitro studies, laboratory techniques and scientific reports related to adhesion process in dental laboratory and published in English were searched using ISI Web of Science, MEDLINE-PubMed, Google Scholar and Scopus electronic databases. The last search was performed on June 30, 2022 without any restriction on the publication date.

2. Basic terminologies (Noort, 2013)

Adhesion: The force that binds two dissimilar materials together when brought into close contact.

Cohesion: The attraction between similar atoms or molecules within a substance.

Adhesive: The substance that binds the two materials.

Adherend (substrate): The surfaces of the materials.

Interface: The location at which the substrate meets the adhesive is crucially important for the success or failure of an adhesive bond.

3. Adhesion principles

To better understand the adhesion mechanism, some surface state principles need to be redefined to encompass all the interactions that aid in uniting two main bodies. The surface state incorporates all the chemical, structural, and topographic features of the material. In practice, the surface is always filled with flaws and variations (Zhao et al., 2021). Wettability is the first and most appropriate timeframe for any adhesion mechanism to succeed. An adhesive cannot establish micromechanical interlocks, chemical bonds, or interpenetrating networks with a surface unless it can make intimate contact, spread over it, and infiltrate the micro- and sub-microscopic imperfections by capillary attraction. These conditions are satisfied if the adhesive wets the surface (Noort 2013; Shen et al., 2022). In general, increasing the surface energy of substrates improves their wettability (e.g., synthetic materials in dental laboratories) (Noort, 2013).

The wettability of an adhesive can be described by the contact angle formed on the solid bonding surface. A 0 °contact angle implies full wetting, $<$ 90 °implies mostly wetting, and $>$ 90 °and 180 °imply mostly less wetting and no wetting at all, respectively. In general, a high contact angle implies a hydrophobic or low-wettability solid surface, whereas a low contact angle indicates a hydrophilic or high-wettability solid surface (Menzies and Jones, 2010).

4. Mechanism of adhesion

There is no single hypothesis that can explain adhesion; however, it is typically classified as mechanical, physical, or chemical, and more frequently, as a combination of all of these (Noort 2013; Zhao et al., 2021).

4.1. Mechanical adhesion

Mechanical adhesion occurs when two distinct phases are attached to one another solely by mechanical force. This form requires the presence of surface imperfections, which provide microscopic undercuts through which the adhesive can penetrate before setting, resulting in the mechanical interlocking of components (Noort 2013; Zhao et al., 2021). Although mechanical adhesion is the foundation of most current adhesive dentistry, the achievement of good adhesion between smooth surfaces demonstrates that mechanical interlocking theory is not widely applicable (Kinloch, 1987).

4.2. Physical adhesion

Physical adhesion implies short interaction distances. This adhesion aspect is related to the micro- or macro-bonds of the mechanical anchors via low link (hydrophilic or hydrophobic) physical adsorption. As the molecules remain chemically intact on the surface, this type of bonding is quick and reversible. However, the adhesion is weak and inappropriate when a permanent bond is vital (Noort 2013; Zhao et al., 2021).

4.3. Chemical adhesion

Chemical adhesion occurs when the surface atoms of an adhesive and substrate create ionic, covalent, or hydrogen bonds. The ionic or covalent bonds formed between the adhesive and substrate result in strong binding of the two materials if they can form a compound at their interface or union. When hydrogen bonding occurs, a hydrogen atom in one molecule is attracted to an electron-donor atom, such as nitrogen or oxygen in another molecule, creating a weaker bond (von Fraunhofer, 2012). Cohesive forces within the material are caused by chemical bonding (Noort 2013; Zhao et al., 2021).

4.4. Diffusive adhesion

Diffusive bonding occurs when atoms from one surface penetrate another while remaining attached to the original surface. This adhesion mechanism is involved in the fabrication of a PFM crown, where porcelain is fused to the metal. As diffusive adhesion necessitates atomic species interaction between two surfaces, the longer the two surfaces may interact, the more diffusion occurs, and as a result, the stronger the adhesion between them (von Fraunhofer, 2012).

4.5. Dispersive adhesion

The surfaces of the two materials are maintained together by van der Waals forces in dispersive adhesion or physisorption. The latter are the attractive forces between two molecules, each of which has a small positive and negative charge region, causing the molecules to be polar in relation to the average charge density of the molecule. It should be noted that larger and/or more complex molecules may have multiple poles (regions of greater positive or negative charge) (von Fraunhofer, 2012).

5. Surface conditioning in dental laboratory

The bond between the underlying substructure and outer veneer must be strong and durable for a successful bilayered restoration (Jongsma et al., 2012). Variations in the properties between the two layers and the surface treatment in mechanical bonding, as well as the materials utilized in chemical bonding, are factors that could affect this bond (Goldstein 1989; Dudea et al., 2014).

Surface conditioning of indirect restorative materials, such as metals, metal alloys, ceramics, resin-matrix ceramics, and polymers, is a vital step in activating the substrate surface for long-term adherence with veneering materials. In dental laboratories, several surface treatments have been applied (Matinlinna et al., 2018). The most common are airborne-particle abrasion (Lung, 2014), pyrochemical silica coating (Janda et al., 2003, Matinlinna and Vallittu, 2007), tribochemical silica coating (Ho et al., 2015; Khan et al., 2016), and chemical treatments using acids and bases (Ban et al., 2006; Lung et al., 2010). The less common are selective infiltration etching (Aboushelib et al., 2010, Aboushelib and Matinlinna 2011), nano-structured alumina coatings (Jevnikar et al., 2010), chemical vapor deposition (Piascik et al., 2009), laser treatment (Akyıl et al., 2010), the internal coating method (Kitayama et al., 2010), sol–gel coating (Lung et al., 2013), plasma fluorination (Piascik et al., 2011), nano-silica coating (Lung et al., 2015), and silicone-based coating (Lung et al., 2015).

Composite resins and porcelain are used as veneering materials in the laboratory to mask the substructure restorative materials (Goldstein, 1989). Porcelain offers outstanding aesthetic, strength, and wear resistance, as well as the ability to hold a limited quantity of bacterial plaques. However, this method has several significant drawbacks. Opposing natural teeth are frequently worn down by porcelain, which is more brittle and tougher than natural enamel. Furthermore, porcelain manipulation is time consuming and requires dexterity (Lee et al., 2009). The advantages of composite resin as a veneering material for substructures include ease of handling and repair both in the laboratory and chairside in clinics, wear similar to that of natural teeth, color stability and aesthetics, and biocompatibility with surrounding tissues (Dudea et al., 2014). Clinicians have also reported numerous issues with composite resins, including discoloration, micro leakage, and low bond strength to metal surfaces. However, resin-veneered crowns, such as those used in telescope crowns, fixed prostheses, and implant prostheses, are still in demand (Choo et al., 2015).

5.1. Metal and metal alloys

Noble alloys, which are made up of precious metals such as gold and silver, and non-noble alloys, which are made up of non-precious metals such as nickel, cobalt, chromium, and titanium, are two types of alloys used in dentistry. Although previous studies have demonstrated effective and durable adhesion of non-noble alloys, no superficial conditioning strategy capable of promoting effective and stable adhesion has been verified for noble alloys (Andreatta-Filho et al., 2015).

Macromechanical retentions, such as undercuts, beads, loops, wires, posts, and meshes, are commonly used to bond metallic substructures to composite resins. However, this method produces a larger framework and creates a 20 µm gap at the resin-metal interface, resulting in resin discoloration and separation. Sandblasting, electrolytic etching, and chemical etching techniques have been utilized to generate microroughness on metals to overcome these imperfections. However, as all these approaches rely on mechanical bonding, microleakage cannot be completely eliminated. As a result, the chemical bonding procedures using a metal primer, silicoating, heat treatment, and tin plating have been employed (Lee et al., 2009).

Metal substructures in fixed dental prostheses (FDP) are often fabricated with Co-Cr alloys with excellent clinical success. In recent years, titanium (Ti) has been used as a prosthesis material because of the development of casting and surface treatment techniques, and advantages such as adequate corrosion resistance, excellent biocompatibility, low density and its suitability for use in patients allergic to nickel, cobalt or chromium. However, low bond strengths between Ti and composite veneering systems have been reported. To overcome this limitation, several surface conditioning methods based on macro- and micromechanical retention, chemical bonding, or a combination of both have been proposed (Almilhatti et al., 2013). Specifically, silicoating, metal conditioners, sandblasting, and titanium nitride (TiN) coatings have been applied (Lee et al., 2009).

The success and durability of porcelain-fused-to-metal prostheses depend on the bonding between the porcelain and metal. The metal-ceramic bonding appears to result from chemical bonding, mechanical interlocking, van der Waals forces, and compressive bonding, although chemical bonding dominates (Bagby et al., 1990). Chemical bonding with metals can change when an oxide layer forms on the surface (Li et al., 2017). Porcelain chipping or fracture is a serious problem that causes both functional and aesthetic issues. Increasing the wettability of the metal by porcelain and regulating the thickness of the oxide layer are the two crucial parameters that have been proposed to improve the bonding between the base metal alloys and porcelain. Sandblasting, oxidation heat treatment, laser etching, acid etching, bonding agent application, mechanical roughness with carbide burs or diamond tips, and a combination of surface treatments are among the surface treatments recommended for porcelain-fused-to-metal prostheses (Hamza et al., 2019).

Airborne-particle abrasion of bonding surfaces increases the surface energy by improving the wettability of the material and, consequently, the adhesion strength through micromechanical bonding. The most commonly used particles for air-abrasion are aluminum oxide (Al_2O_3) with various grit sizes. This process is affected by the particle size of Al_2O_3, application time, air pressure value of the abrasion device, and distance of the abrasion device from the material surface (Coskun et al., 2018). There is no exact protocol for the use of airborne-particle abrasion, although a recent study has recommended that 75 psi for 30 s with a particle size of 110 µm from a distance of 20 mm be applied for the surface roughening of Ni-Cr alloys (Coskun et al., 2018; AlMutairi et al., 2021; AlMutairi et al., 2021).

It has been reported that using silane coupling agents after air-particle abrasion improves the bond strength. Following the application of a silane coupling agent to the substructure surface, siloxane-to-metal linkage is produced; however, the formation is highly dependent on the metal characteristics and surface chemistry (Yanagida et al., 2009; Jin et al., 2015). In contrast, metal and alloy primers have been recently utilized to bond resin composites to metal alloys, and have demonstrated similar or better adhesion strengths than silane coupling agents. Phosphate esters, carboxylic acids, or acid anhydrides for base metal alloys, and thione or thiol for noble metal alloys are common reactive primer components present in metal or alloy primers (Di Francescantonio et al., 2010; Nima et al., 2017).

5.2. Ceramics

Ceramic is increasingly being used as a restorative material in place of composite resins and metal-ceramic restorations. The development of new ceramic technologies and a strong and durable adhesion can be credited to this trend. Composite resins can be bonded to ceramic substructures, such as zirconia, which are regarded as unetchable with hydrofluoric acid because of their glass-free characteristics. This can be accomplished by utilizing primers that contain adhesive phosphate monomers, which can chemically bond to metal-oxide-containing ceramics while also improving their surface wettability, thereby improving the adhesion (Blatz et al., 2003; Meyer-Filho et al., 2004; Kern, 2009; Kern, 2015, Blatz et al., 2016; Polat et al., 2021).

Airborne-particle abrasion with silica-coated alumina particles to create a silica layer before using silane coupling agents for bonding has been attempted to change the zirconia surface properties (Matinlinna and Vallittu, 2007). This change in the zirconia surface can enhance the bonding surface area and improve the mechanical bonding with other materials (Guazzato et al., 2005; Özcan and Volpato, 2015). However, airborne abrasion is thought to induce microcrack propagation in zirconia, resulting in weakening of the core material (Ural et al., 2011; Özcan and Volpato, 2015; AlMutairi et al., 2021). A few studies have concluded that the use of airborne-particle abrasion with alumina particles followed by universal primer application is the best method for bonding composite resin to zirconia (Kern, 2009; Yun et al., 2010; Attia and Kern, 2011; AlMutairi et al., 2021).

With the introduction of the zirconia framework, all-ceramic crowns and fixed partial dentures in the molar area have become conceivable, as zirconia, particularly tetragonal zirconia polycrystal (TZP), has high fracture strength and toughness (Lüthy et al., 2005). All-ceramic restorations utilizing veneering ceramics bonded to a TZP framework, and on the other hand, chipped at a rate of 13 % and 15.2 % after 3 and 5 years, respectively (Sailer et al., 2006; Sailer et al., 2007). Metal ceramics, on the other hand, are said to have a fracture rate of only 8 %–10 % after ten years (Scurria et al., 1998). The presence of a monoclinic phase of zirconia at the zirconia-veneering porcelain interface may result in the formation of microspaces, which could lead to crack propagation and endanger adhesion strength (Aboushelib et al., 2006).

Therefore, it was necessary to reinforce the adhesion surface to achieve durable adhesion between the veneering ceramics and TZP framework. The adhesion mechanisms between the veneering ceramics and TZP framework include chemical bonding, mechanical fitting, and shear stress, based on the difference in the thermal expansion coefficient between the veneering ceramics and TZP (Tada et al., 2012). The adhesion strength is influenced by many factors, such as surface roughness, use of linear porcelain, and heat treatment of TZP (Tada et al., 2012; Cevik et al., 2016).

According to Tada et al. (2012), the adhesion strength between veneering ceramics and TZP can be improved by increasing the strength of the veneering ceramics themselves, resulting in less chipping. Additionally, the authors determined that chipping may be reduced by creating a coping method for veneering ceramics of uniform thickness, such as a metal ceramic crown, as well as by contouring the veneering ceramics to avoid stress concentration. To improve adhesion strength and prevent delamination of the veneering porcelain, Cevik et al. (2016) recommended treating zirconia copings with airborne particle abrasion, Nd:YAG laser, grinding, or the selective infiltration approach for reliable bonding.

5.3. Polymers

High-performance polymer materials are at the forefront of dental research with the goal of improving framework properties and potentially lowering the overall cost of prosthetic tooth rehabilitation (Alexakou et al., 2019). Polyaryletherketone (PAEK) family based polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) polymers have been introduced as high-performance restorative materials in dentistry, with both materials demonstrating high strength that exceed the minimum standards for dental thermoplastic restorative materials (Papathanasiou et al., 2020; Alqurashi et al., 2021; Qin et al., 2021; Alsadon et al., 2022). PEEK was the first PAEK-based material to be used in dentistry for the fabrication of dental implants, removable partial dentures and obturators, fixed partial dentures and crowns, and orthodontic wires (Maekawa et al., 2015; Tada et al., 2017; Alsadon et al., 2022). Owing to its preferred properties, PEEK has been suggested and studied as a possible replacement for clinically well-established titanium, zirconia, and acrylic restorative materials (Schwitalla and Müller, 2013). However, clinical studies to support the longevity of PEEK for fixed and removable prosthesis restorations are scarce (Najeeb et al., 2016).

Despite their desirable mechanical properties and biocompatibility, the poor translucency and greyish color of PEEK and PEKK preclude their use as monolithic dental restoration materials. Therefore, to improve their appearance, these materials frequently require aesthetic veneer coverage (Papathanasiou et al., 2020; Alsadon et al., 2022). However, the adhesion to veneer materials may be hampered because of their high resistance to etching chemicals and low surface energy, (Najeeb et al., 2016; Papathanasiou et al., 2020; Villefort et al., 2021; Alsadon et al., 2022).

The conventional and economical surface treatment for thermoplastic materials is air-particle abrasion, which is commonly recommended by PEEK manufacturers (Villefort et al., 2021). The manufacturer of Pekkton® ivory (Cendres + Mé taux SA, Switzerland) recommends air-particle abrasion with 110 µm Al_2O_3 particle under 0.2 MPa pressure, followed by the application of composite primers for the PEKK surface to obtain durable adhesion with the composite resin. The particle abrasion followed the same procedure as that used for the metal substructure. In a recent study by Gouveia et al. (2021), it was concluded that the shear bond strength of composite resin to PEEK and PEKK surfaces treated with 110 µm aluminum oxide airborne-particle abrasion was improved. The authors further stated that the manufacturing process (milled or heat-pressed) had no effect on the adhesion strength of PEKK subjected to identical bonding techniques. In another study by Alsadon et al. (2022), the adhesion strength values of PEKK materials were much lower than those of PEEK and significantly higher than those of conventional zirconia and Ni-Cr alloy materials. The authors observed a significantly positive association between surface roughness and adhesion strength; however, they reported that the association could be due to the material or roughness.

Another recommended surface treatment procedure is a tribochemical silica coating (Rocatec™, 3 M ESPE, USA). Furthermore, the surface modifications of PEEK using chemical and physical agents such as 98 % sulfuric acid etching, hydrofluoric acid etching, a mixture of sulfuric acid and hydrogen peroxide (piranha solution), and treatments with inert gas plasma and argon plasma are also explored. These surface treatment methods have demonstrated favorable adhesion performance of PEEK to composite resin (Villefort et al., 2021).

5.4. Acrylic resins

The aesthetic considerations of poly-methyl-methacrylate (PMMA) remain a concern despite improvements in its physical properties. The availability of PMMA shades limits teeth with a color-contrast effect or exceptional translucency. By layering a restorative resin composite over PMMA to improve the aesthetic quality, a combination of PMMA and light-cured resin composite has been proposed. Furthermore, composite resin availability in different shades, better aesthetic outcomes, easy handling, and good wear resistance make it a widely used restorative material. Therefore, altering the PMMA restorations with resin composites for aesthetic reasons is a viable option. The thin layer of resin composite successfully adhered to the PMMA would provide a satisfactory aesthetic outcome as well as cost reduction compared to complete composite resin restorations (Aksornmuang and Tiangtrong, 2021). It has also been touted as a rapid, easy, and low-cost procedure for creating composite occlusal surfaces on complete and partial dentures (Vergani et al., 2000).

The surface preparation of acrylic resin is critical for ensuring high durability and strong adhesion between the acrylic resin and composite resin. Chloroform improves the quality of adhesion areas during denture repair. The same is true whether a composite resin or denture base resin is used for bonding. However, because chloroform is a carcinogen, caution should be exercised when applying it to surfaces (Vergani et al., 2000).

A previous study demonstrated that wetting of the acrylic resin surface with methyl-methacrylate (MMA) monomer followed by application of light-polymerized composite resin results in a durable bond between the acrylic resin and composite resin (Vergani et al., 2000). Another study reported durable adhesion using commercially available adhesive bonding agents (HC primer, Scotchbond Universal, or Luxatemp glaze and bond) after wetting the acrylic resin surface with MMA (Aksornmuang and Tiangtrong, 2021).

6. Conclusion

Applying proper surface treatment is of paramount importance in enhancing the adhesion between the substructure restorative material and the veneer. Dental technologists should be aware of the advantages and disadvantages of different surface treatment methods available for each restorative material category. Furthermore, understanding the physical characteristics of restorative materials will provide adequate knowledge for the application of the most reliable adhesion techniques in dental laboratories.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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