

# Advances in Bonding Technology for Zirconia Ceramic Restorations

Bohan Jiang<sup>+</sup>, Congcong Li<sup>+</sup>, Yuxiang Fang, Jianing Nie, Lifang Feng<sup>\*</sup>

North China University of Science and Technology, Tangshan 063210, China

---

## Abstract

Zirconia ceramics have been extensively employed in clinical restorative treatment because of their unique biocompatibility and aesthetic properties. This material not only possesses excellent optical and mechanical properties but also demands a reliable bonding effect for better clinical application. Owing to its chemical inertness, the bonding effect of zirconia ceramics is inferior to that of silicate-based ceramic materials. Since the bonding performance of the material is directly related to the long-term efficacy of the restorations, the enhancement of zirconia ceramic restoration bonding has become an active area of research in recent years. Following the optimization of bonding resins and the continuous improvement of bonding technologies in recent years, the bonding of zirconia ceramic materials has been significantly enhanced. This paper reviews the selection of bonding agents for zirconia ceramic restorations, the surface treatment of zirconia ceramic materials, and the treatment of the bonding surface of the dentin, aiming to provide a basis for its clinical research and application.

## Keywords

Zirconia Ceramics; Adhesive Properties; Surface Treatment.

---

## 1. Introduction

Zirconia ( $ZrO_2$ ) ceramics have emerged as one of the most prevalent restorative materials utilized in clinical settings due to their excellent mechanical properties, chemical stability, and biocompatibility. These characteristics address the issues of other restorative materials regarding esthetic properties, potential allergic reactions, MRI interference, and effects on periodontal health.<sup>[1-4]</sup> Ensuring superior biocompatibility to ensure stable use in a moist oral environment, and additionally excellent mechanical properties and robust physicochemical stability to meet different clinical needs<sup>[5, 6]</sup>. Exceptionally high mechanical strength and outstanding wear resistance in zirconia ceramics, bending strength of 900 to 1200 MPa and fracture toughness of more than 2000 N under steady-state conditions, approximately twice as compared to alumina ceramics, and bending strength threefold higher than that of lithium disilicate ceramics<sup>[7, 8]</sup>. A material exhibiting dynamic behavior with toughness due to phase transformation exhibits three crystal structures at atmospheric pressure: the monoclinic, cubic, and tetragonal phases<sup>[9]</sup>. As temperature changes, these three crystalline phases undergo conversion, resulting in surface micro-cracks on zirconia ceramics, affecting its mechanical performance and the service life of the restoration. When the tetragonal phase converts into a monoclinic phase, a martensitic-type phase transition occurs, resulting in expansion of the material, and the material will exhibit microcracks and fragmentation, among other phenomena, thereby impacting subsequent research and use<sup>[10]</sup>. To prevent zirconia's crystal transformation during temperature change,  $Y_2O_3$ , MgO, CaO, etc. are commonly added to zirconia. The  $Y_2O_3$ - $ZrO_2$  solid solution system is currently the most widely used stabilization system for zirconia<sup>[10]</sup>.

Although zirconia ceramics have become an ideal material for clinical restorations due to their excellent physical and chemical properties, the bonding issue of zirconia ceramics remains a key

factor affecting the restorative results. This paper discusses methods to enhance zirconia bond strength through the selection of appropriate bonding agents, optimizing the surface treatment of zirconia ceramics, and enhancing the treatment of the bonding surface of dental tissues, to provide clinical guidance.

## 2. Selection of Bonding Agent

### 2.1 Classification of Bonding Systems

Dentin bonding is based on micromechanical retention of the resin, which is achieved through the processes of acid etching, modification, and bonding. Before dentin bonding, the smear layer is first removed to enhance the surface activity of dentin. Depending on the treatment of the bonding surface, dentin bonding agents are primarily classified into three types: total acid etch bonding, self-etching bonding, and self-bonding systems. Full acid etching bonding involves applying an acid etching agent to the dentin surface, rinsing with plenty of water and air-drying thoroughly after 15-30 seconds. Then, 1-2 layers of bonding agent are evenly applied, air-dried, and then irradiated with a specific light-curing lamp for 20-40 seconds before bonding with a bonding cement. Total acid-etching bonding is complicated, but it has superior bonding performance and is widely used in clinical practice, especially for some poorly cemented restorations. Compared with the full-acid-etch system, the self-etching system does not require the treatment of acid etching agent, and only needs to apply the bonding agent containing acid function, and then use the bonding cement to bond, which simplifies the operation steps, saves time, reduces the dependence on technology, and at the same time reduces the risk of postoperative sensitivity, which is a significant advantage in the clinical application. In addition, the self-adhesive system requires only one step of the functional bonding cement containing acid monomers to achieve chemical bonding, and its bonding strength and durability are jointly determined by the physical properties of the resin cement and the degree of stability of the hydrolysis of the internal acidic functional monomer<sup>[11]</sup>, It is designed for patients who have a good retention of restorations and limited operation. Therefore, the selection of a bonding system should be based on the patient's tooth position, the extent of damage, the type of restoration, and the retention of the restoration.

### 2.2 Bonding Agent Type Selection

Commonly used in clinical practice adhesives for bonding zirconia restorations are typically categorized into the following five categories according to their main components: Zinc phosphate cement, zinc polycarboxylate cement, glass ionomer cement, composite resin-based adhesives, and resin-modified glass ionomer adhesives<sup>[12]</sup>. In addition, there is a new type of bonding material, self-adhesive resin cement, characterized by the ability to be applied directly without surface preparation of the tooth, and capable of withstanding the moisture on the tooth surface to a certain extent<sup>[13]</sup>. Liu et al.<sup>[14]</sup> have studied that, if zirconium oxide is pretreated like sandblasting, and a primer is applied to the dentin surface, then the bonding agent exhibits improved mechanical properties and hydrolysis resistance. Zinc phosphate cement, zinc polycarboxylate cement, and glass ionomer cements exhibit better initial bonding results, but their bond strength decreases significantly after 5000 thermal cycles due to marginal dissolution at the restoration margins<sup>[15, 16]</sup>. Compared to other types of adhesives, resin-based adhesives demonstrate superior bonding properties and lower marginal dissolution rates, which confer significant advantages in the field of dental restorations. Microleakage represents a common challenge in restorative dentistry, and upon occurrence of adhesive dissolution, marginal microleakage will result in compromised marginal adaptation of the restoration, thereby negatively affecting periodontal health. Especially in the bonding of zirconia all-ceramic crowns, resin-based adhesives not only ensure long-term stable bond strength, but also effectively prevent microleakage, further contributing to the preservation of periodontal health. Resin-based adhesives reduce gaps through the formation of a cross-linking structure between the restoration and the abutment by forming resin protrusions in the dentin tubules. This cross-linking structure lowers the modulus of elasticity of the overall system and serves as a stress buffer, thereby enhancing the integrity of the

dentin-bonding interface<sup>[17, 18]</sup>. At the same time, several commonly used resin-based bonding agents were investigated by some scholars. All resin-based bonding agents exhibited superior adhesive performance. KerrOptiBondVersa and MaxcemElite demonstrated the highest bonding strength among resin-based bonding agents<sup>[19]</sup>.

### 3. Surface Treatment of Zirconia Ceramic Tissue Surfaces

#### 3.1 Sandblasting

Sandblasting, to be a widely adopted method, enhances the surface roughness and cleanliness through high-speed blasting with compressed air. However, when the sandblasting pressure exceeds 0.3 MPa, the bending strength of zirconia decreases, while monoclinic crystal phases and micro-cracks form on the surface<sup>[20]</sup>. Kim, H.K et al.<sup>[21]</sup> who studied the surface roughness of 50  $\mu\text{m}$  and 110  $\mu\text{m}$  diameter particles under different sandblasting pressures and sandblasting times concluded that 110  $\mu\text{m}$   $\text{Al}_2\text{O}_3$  particles at 0.2 MPa air pressure sandblasting both increase the surface roughness and improve the flexural strength of zirconia. Sandblasting at higher pressure (0.4 MPa) and larger particle size (250  $\mu\text{m}$ ) may produce microcracks and cause zirconia to degrade and undergo crystalline phase transformation, which reduces the mechanical strength of the oxide ceramics. Inokoshi M et al.<sup>[22]</sup> have shown that the high-speed impact of  $\text{Al}_2\text{O}_3$  hard particles produces irreversible deformation locally, which is prone to produce compressive residual stresses, cracks, and other stresses in the zirconium oxide surface. producing compressive residual stresses, cracks and damage in the near-surface region. Li Xin et al.<sup>[23]</sup> showed that when  $\text{Al}_2\text{O}_3$  blasting was used to enhance the bonding strength of zirconia with resin, a pressure of 0.2 MPa, a particle size of 110  $\mu\text{m}$ , and a treatment duration of 21 s were the most desirable treatment parameters.

#### 3.2 Thermal Acid Etching

The principle of hot acid etching involves using strong acids to chemically react with the surface of zirconia while it is in a heated state. This process removes high-energy atoms from the surface, creating numerous pore structures. As a result, the surface roughness of the material is increased, thereby significantly enhancing the adhesion between zirconia and resin cement<sup>[24]</sup>. Hydrofluoric acid (HF) is widely used in dentistry because of its ability to improve the bonding properties of zirconia and enhance its bond strength with resin cement<sup>[25]</sup>. When compared with concentrated hydrochloric acid, the use of HF results in a greater number of micropores on the zirconia surface, leading to improved bonding with resin cement<sup>[26]</sup>. Some researchers have demonstrated that the surface roughness of zirconia is observed to increase gradually as both the concentration of HF and the duration of treatment are increased<sup>[27, 28]</sup>. However, it was found that the bending strength decreases with prolonged hot acid etching, whereas no significant changes in bending strength were observed during short-term hot acid etching. Despite enhancing the bond strength, hot acid etching treatment exhibits a limitation in its efficacy. To optimize bonding performance while mitigating adverse impacts on bending strength, two hot acid etching protocols are suggested: immersion in a 9.5% HF solution for 60 minutes, or immersion in a 40% HF solution for 5 minutes.

#### 3.3 Coupling Agent

Zirconia coupling agents promote the adhesion of the resin binder to the zirconia surface via the formation of chemical bonds, thereby strengthening the interfacial bond strength and reducing the occurrence of microleakage. Acidic functional coupling agents such as 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) and 4-methacryloyloxyethyl trimellitic anhydride (4-META) are commonly used<sup>[29]</sup> and Phosphorylated methacrylate MP<sup>[30]</sup> among others. 10-MDP is the most widely used agent. The phosphate group in the MDP molecule can react with the hydroxyl groups on the zirconia surface to form a stable chemical bond. Meanwhile, the methacryloyl group in MDP can participate in the subsequent resin polymerization reaction, firmly bonding zirconia to the resin material. Additionally, the chemical interaction between MDP and zirconia further enhances the adhesive strength, providing stronger assurance for the reliable bonding of

zirconia ceramics in clinical settings<sup>[31, 32]</sup>. The incorporation of MDP not only strengthens the bond between zirconia ceramics and resin but also minimizes microleakage and extends the service life<sup>[33]</sup>.

### 3.4 Silicon Coating

Zirconia ceramics exhibit unique surface properties and are virtually free of silica due to the absence of a glassy phase, making it challenging for chemical reactions to take place with the decorative ceramic layer. To address this challenge, a silica coating technique was developed to apply a silica layer onto the zirconia surface, enabling silanisation to improve the bonding properties between the ceramics<sup>[34]</sup>. Tribo-chemical silicon coating (TSC) involves alumina particles coated with zirconia that undergo sandblasting. Sandblasting roughens the ceramic surface, after which silica is applied and combined with silane coupling agents to form a siloxane chemical bond between the resin cement and the silica. This improves the wettability of the zirconia ceramic surface and enhances its adhesive properties with the resin cement. TSC has been acknowledged as an alternative to traditional sandblasting, complemented by 10-MDP<sup>[35]</sup>. Additionally, SiCl<sub>4</sub> vapour silica coating technology was developed based on an earlier process involving chlorosilane treatment of zirconia surfaces. Using vapour deposition technology, SiCl<sub>4</sub> vapour and water vapour are skillfully combined to deposit a thin silica-like coating on the zirconium oxide surface, providing adhesion sites for subsequent bonding<sup>[36]</sup>.

### 3.5 Selective Etching (SIE)

Selective etching begins with the deposition of a silica-based material onto the surface of zirconia. This layer is then subjected to a melting process at 960°C to promote the diffusion of the material into the zirconia's interior. Subsequently, the glass component is removed through hydrofluoric (HF) acid etching. The results of the work of Cheung et al<sup>[37]</sup> scholars have shown that the surface of zirconia treated by selective etching has formed a porous structure, and has a high surface energy, which is very helpful for the infiltration of resin cementum. The bond strength was shown to be excellent both before and after the hot and cold cycles. However, Saade et al.<sup>[38]</sup> reported contrasting findings in their study, indicating that the SIE group exhibited a notable reduction in bond strength following aging treatments, including water storage and enzymatic degradation. Therefore, the long-term efficacy of the SIE method requires further validation through additional studies.

### 3.6 Low-temperature Plasma

Under the conditions of an atmospheric-pressure cold plasma jet, a wide variety of reactive species are present, effectively activating the material surface. While preserving the material properties, the plasma treatment enhances the polar groups on the zirconia surface, particularly the introduced hydroxyl groups, which can improve adhesion via both chemical bonding and physical adsorption<sup>[39]</sup>. Oxygen, argon, and other gases have been demonstrated to produce plasma under low-temperature or non-thermal conditions, thereby enhancing the hydrophilicity of the zirconia surface, improving surface wettability, and reinforcing bonding properties<sup>[40]</sup>. Liu et al.<sup>[41]</sup> showed that treated zirconia ceramics showed an increase in shear strength, with the average shear bond strength comparable to the average shear bonding strengths obtained by conventional clinical protocols with HF etching and silane coupling agent coating on lithium silicate plates. The average shear bond strength was found to be comparable to that achieved using HF etching and silane coupling agent coating on lithium silicate plates within conventional clinical protocols, as reported by Valverde et al.<sup>[42]</sup> concluded that the contact angle of zirconia ceramics was significantly reduced following plasma treatment. Subsequent bond strength experiments further confirmed that the treated zirconia ceramics exhibited a substantial increase in bond strength. In conclusion, low-temperature plasma can enhance the bonding properties of zirconia with resin-based materials.

### 3.7 Laser

The principle of laser treatment is to utilize laser energy discharge to cause microbursting, vaporization, or melting of the ceramic surface layer, thereby facilitating the formation of mechanical interlocking with resin-based restorative materials and enhancing the surface roughness of zirconia

[43, 44] . Nd:YAG laser treatment can alter the surface roughness of zirconia; however, the heat generated during the process may induce internal cracking, residual stresses, and phase transformation into the monoclinic crystal structure, thereby negatively impacting the bonding quality [44] . Er:YAG laser treatment at an output power of 2W has a similar effect on surface roughness as alumina sandblasting; however, cracks and surface defects are also observed on the ceramic material [45] . Both Er:YAG laser and Nd:YAG laser treatments enhance the roughness of zirconium oxide surfaces and improve bonding strength, yet they do not surpass the efficacy of sandblasting treatments [46] . Yb:YAG, as an ultrashort pulsed laser, exhibits extremely high processing speeds and can be utilized for treating zirconium oxide surfaces. Yb:YAG is an ultrashort pulsed laser that efficiently removes overheated material in minute quantities at extremely high speeds. The removal process is so precise that there is little mechanical or thermal damage to the rest of the sample, and studies by ESTEVES-OLIVEIRAM et al. [47] have shown that Yb:YAG laser treatments show better results than treatments using friction-chemical silica coatings and alumina sandblasting. Today, femtosecond lasers are the shortest pulses that can be used, and TubaYilmaz-Savas et al. [48] have shown that femtosecond laser treatment of zirconia surfaces produces a more regular pit structure than Er:YAG lasers, which is a unique advantage in terms of bonding properties. In addition, the bonding effect can be further enhanced by combining femtosecond laser treatment with friction chemical silicon coating technology [49] .

### 3.8 Polydopamine (PDA) Composite Coatings

PDA coatings are dopamine-derived mussel mimetic materials with extremely broad and strong interfacial binding capabilities, as well as secondary reaction properties. In the medical field, it is regarded as a highly efficient additive for material coatings, and its structural features, formation mechanism, and thermodynamics have always been a popular direction for researchers to study [50-52] . Several studies have demonstrated that PDA coatings can significantly improve the bonding strength between zirconia and resin cement [53, 54]. However, the long-term stability of this approach remains to be investigated. The adhesion of the zirconia surface to the PDA coating can be primarily attributed to two mechanisms. Firstly, zirconium ions or their oxides exhibit a strong chelating effect with the catechol groups present in PDA. Secondly, the quinone groups formed during the self-polymerization of PDA interact via  $\pi$ - $\pi$  stacking with the benzene rings, while the catechol groups can also undergo chemical reactions with the amino and hydroxyl groups [55-58] .

### 3.9 Melt Sputtering Technology

The process begins by introducing a suspension containing zirconia particles into a high-pressure vessel, where bubbles are generated. These bubbles are subsequently ejected onto the surface of the zirconia material before the sintering step. When the particles in the suspension come into contact with the material surface, they firmly adhere to it, forming a rough surface layer. Following the sintering process, the particles bond with the original zirconia surface, creating grooves that provide a mechanical interlocking effect. This not only increases the surface roughness but also enhances the mechanical retention of the material [59] . Compared to conventional sandblasting, fusion sputtering does not cause defects such as scratches or grooves on the zirconia surface. Consequently, the fracture resistance of the material is not reduced. The results of the research conducted by scholars such as Ali et al [60] show that when comparing the microscopic shear strength of fusion sputtering treatments and alumina air abrasion treatments, the values of the former are significantly higher. In addition to its excellent bonding strength, the melt sputtering technique also demonstrates superior durability and effectively resists microleakage after aging. However, it has some limitations: the raised microbead structure increases the zirconia surface thickness by approximately 10 microns on average, potentially causing zirconia restorations to experience difficulty in seating when used [59] .

### 3.10 Number of Zirconia Sintering Times

The number of sintering times of zirconia ceramics has a significant effect on their bonding properties with resin cement. Oğuz et al. [61] showed that for 3% yttrium oxide-stabilized tetragonal zirconia

ceramics (3 mol% yttrium oxide-stabilized tetragonal zirconia polycrystals, 3Y-TZP), after 5 to 10 cycles of sintering, the bond strength with resin cements containing 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) was significantly higher than that of the second sintering group. For partially stabilized zirconia (5Y-PSZ), moderate sintering (1 to 3 cycles) enhanced the microshear bond strength, while excessive sintering (5 to 10 cycles) led to a decrease in bond strength. Currently, the relationship between the number of sintering cycles of translucent zirconia and its bonding performance has received limited attention, and the underlying mechanisms remain unclear. Further research is needed to investigate how different sintering process parameters affect the microstructure of the material's surface and the chemical activity of the bonding interface.

### 3.11 3D Printing Technology

3D bioceramic printing technology is an innovative manufacturing process that constructs bioceramic structures through a layer-by-layer printing method. Zirconia inkjet-based custom 3D printing technology enables high-precision customization of arbitrary shapes, the production of one-piece zirconia components, a rapid printing process that requires no human intervention, and ensures no damage to printed parts. Furthermore, it allows for nearly isometric rendering of intraoral scanning models. In the field of bioceramic 3D printing technology, Yin Lu et al. [62] investigated the impact of 3D-printed zirconia patterning design and surface pretreatment on bonding performance. They specifically designed micropores on the surface of zirconia specimens and conducted experiments using various surface pretreatment methods, including blank control, sandblasting, sandblasting + additional treatments, and sandblasting + silica dioxide coating. The results demonstrated that the different surface pretreatment methods and the number of micropores significantly influenced shear bond strength and exhibited interactive effects. However, the study also noted several limitations in improving bonding performance through zirconia 3D printing, including the absence of flexural strength tests, uncertainty regarding the effect of micropore depth and distribution shape on bonding strength, unsatisfactory bonding areas of specimens, lack of comparisons with other surface pretreatment methods, and the inability to fully simulate the intraoral environment. In the future, it will be essential to integrate bioceramic 3D printing technology with emerging trends in material property optimization, printing precision enhancement, standardization and quality control improvement, and intelligent and personalized production. This integration should involve conducting in-depth research, optimizing microporous design, clarifying the influence of relevant factors, and identifying the optimal treatment method to enhance the bonding performance of zirconia, thereby facilitating its broader application in clinical oral prosthetics.

## 4. Treatment of Dental Tissue Bonding Surfaces

### 4.1 Sandblasting:

Enhancing the bonding between resin materials and teeth can be achieved by air-blasting the dentin surface. This technique creates a rough and uneven surface on the dentin, thereby creating favorable conditions for resin-tooth bonding. Acid etching to remove the tarnished layer is essential following air-blasting treatment. Clinical studies demonstrate that, when combined with a self-etching adhesive system, this approach is straightforward, efficient, and effective [63].

### 4.2 Acid Etching

Acid etching removes the tarnish layer and increases surface roughness, thereby enhancing bonding performance. Existing bonding systems can be classified as either acid-etch-rinse or self-etch types. Dental tissues are typically pretreated with phosphoric acid or hydrofluoric acid. A widely applicable and user-friendly general-purpose bonding agent remains the self-acid-etching type, but its weak acidity limits its efficacy in dentin surface treatment. Combining the acid-etch-rinse mode with universal bonding agents improves their bonding efficacy across various dental tissues. Pre-etching enamel with 37% phosphoric acid prior to applying a general-purpose bonding agent enhances both immediate and long-term bonding. For fluorosis enamel bonding, an extended action time of the self-

etching bonding agent, along with gentle brushing, can exceed the bond strength of conventional methods. Microstructurally, sclerotic dentin exhibits uneven mineralisation, variable thickness, blocked tubules, and disordered crystal arrangements. These characteristics hinder adhesive penetration and bonding layer formation [64]. General-purpose bonding agents are suitable for hardened dentin with a selective acid etching pattern and caries-affected dentin where acid etching has limited impact on bond strength [65].

### 4.3 Photoradiotherapy

Photoradiotherapy is based on the principle of photothermal action and is able to activate many different types of photosensitisers. In practice, each type of photosensitiser demonstrated enhanced bond stability of the bonding surface. It was tested that the shear strength of dentin treated with photosensitisers such as camphorquinone and benzophenone were all higher than that of dentin treated with H<sub>2</sub>O<sub>2</sub> only. Specifically, two photosensitisers, curcumin and indocyanine green, were particularly effective in enhancing elastomers, an advantage that was well demonstrated in the assay where shear bond strength was the measure [66]. Differences in the various methods, powers, frequencies, and durations can lead to differences in treatment outcomes. Therefore, further research is still needed on the specific parameters of photoradiotherapy in terms of ensuring safety and sterilisation [67].

### 4.4 Lasers

Er: YAG laser treatment of dentin surfaces significantly improves their adhesion. LIBER-KNEČA et al. [68] used the Nd:YAG laser together with a calcium potassium phosphosilicate bioactive material. The contact angle of the dentin surface decreased significantly. Laser irradiation of the dentin tubules resulted in fusion, recrystallization, and deposition of the bioactive material on the surface, collectively enhancing the wetting properties of the dentin surface. Considering the humid environment of dentin, enhanced wettability improves adhesive spreading, penetration into demineralized collagen fibers, and tubule infiltration, thereby promoting the formation of high-quality hybrid layers and resin tags [68].

### 4.5 Suction

Dentin, which contains high organic matter and features dentin tubules with fluid flow inside, poses challenges for bonding [69]. Ruishen, Zhuge et al. [70] demonstrated that applying negative pressure during dentin bonding enhances the penetration of resin monomers, thereby improving bonding efficacy. The negative pressure technique maintains the surface morphology of zirconia while synergistically enhancing the bonding strength when combined with sandblasting and 10-MDP agents through air expulsion, leading to a more robust and durable bond.

### 4.6 Chelating Agent (Ethylenediaminetetraacetic acid, EDTA)

EDTA is mild, chelates metal ions, and contains four carboxylic acid groups. When EDTA is applied to dentin, it selectively and stably chelates Ca<sup>2+</sup>, removes hydroxyapatite [71], and improves its resistance to degradation. In vitro studies conducted by researchers revealed that combining treatment of dentin with 18% EDTA for 90 seconds, followed by 37% phosphoric acid for 15 seconds, substantially improved the initial adhesive strength between dentin and bulk resin. However, after one year of artificial aging tests, no significant long-term benefits were observed [72].

### 4.7 Biomineralisation Technology

Biomineralisation refers to the formation of complex structures of inorganic minerals in living organisms under the regulation of specific biomolecules (e.g. proteins, polysaccharides, etc.). Proanthocyanidins were applied to mimic glycosaminoglycan biological functions, and the bridging structure formed between polyacrylic acid (PA) and collagen fibres was verified through the application of infrared Fourier spectroscopy, and it was found that PA was able to form inter-fibre bridges to support the collapsed collagen network [73], promote the regeneration and repair of tooth hard tissues, and enhance the bonding of regenerated hard tissues with materials such as zirconia.

Thus, the mineralization of dental tissues using specific biomolecules is anticipated to enhance the bonding between dentin and zirconia restorations.

## 5. Summary and outlook

Resin-based adhesives stand out for their use with zirconia, as they exhibit a low dissolution rate, excellent sealing at the margins, and superior bonding performance and periodontal health maintenance. Emerging research is also underway on novel zirconia adhesives. In the zirconia ceramic tissue surface treatment, techniques such as sandblasting, thermal acid etching, and laser treatment each have their advantages. Sandblasting requires precise pressure control, thermal acid etching demands careful timing, and laser treatment varies based on type and parameters. Additionally, selective etching and low-temperature plasma treatments show promise, but several challenges remain unresolved. The bonding surfaces of dental tissues are commonly treated with sandblasting and acid etching to enhance bonding properties. The bonding strength of zirconia ceramic restorations is influenced by various factors, including material properties, clinical procedures, and the oral environment.

Currently, research on the bonding technology of zirconia ceramic restorations has achieved certain progress, but there are still many challenges. In the future, research on zirconia ceramic bonding technology is expected to achieve breakthroughs in the following directions:

Firstly, developing new high-performance adhesives to further enhance bond strength and durability while reducing costs to meet more clinical requirements;

Secondly, optimizing the existing surface treatment technology to address issues related to the long-term effectiveness of SIE, the enhancement of adhesive properties using 3D printing technology, etc., improving the technical details, and enhancing the stability and repeatability of the technology, and developing more efficient and safer new surface treatment technologies;

The third is to conduct in-depth research into the long-term influence mechanisms of oral environmental factors on adhesive strength, in order to develop more targeted protective measures and extend the service life of restorations in the oral environment;

The fourth is to integrate emerging technologies such as artificial intelligence and big data to accurately analyse the impact of different factors on adhesive strength and achieve personalized restorative programme design, to improve the clinical treatment effect of zirconia ceramic restorations and provide patients with better oral restorations.

## Acknowledgments

Supported by the Graduate Student Innovation Fund of North China University of Science and Technology: 2024S33.

## References

- [1] CHEĆIŃSKA K, CHEĆIŃSKI M, SIKORA M, et al. The effect of zirconium dioxide ( $ZrO_2$ ) nanoparticles addition on the mechanical parameters of polymethyl methacrylate (PMMA): A systematic review and meta-analysis of experimental studies[J]. *Polymers*, 2022, 14(5):1047.
- [2] DU Q, CUI T, NIU G, et al. Improving bond strength of translucent zirconia through surface treatment with  $SiO_2$ - $ZrO_2$  coatings[J]. *Operative Dentistry*, 2023, 48(6): 666-676.
- [3] KUNRATH M F, GUPTA S, LORUSSO F, et al. Oral tissue interactions and cellular response to zirconia implant-prosthetic components: A critical review[J]. *Materials*, 2021, 14(11):2825.
- [4] Fan G R, Su H J, Zhang, J., et al. Research progress on the reliability, preparation technology and clinical applications of zirconia ceramics for dental use[J]. *Journal of the Chinese Ceramic Society*, 2018, 46(9): 1263-1272.
- [5] Xuan L, Xu Y W. The effects of service environment on the reliability and fatigue performance of dental zirconia ceramics[J]. *Journal of Practical Stomatology*, 2021, 37(6): 749-752

- [6] Zhou Y G, Dong B, Yue X W, et al. Micro-scale grinding force of dental zirconia ceramics[J]. Journal of Northeastern University Natural Science, 2020, 41(4): 557-562.
- [7] LIU C, ESER A, ALBRECHT T, et al. Strength characterization and lifetime prediction of dental ceramic materials[J]. Dental Materials, 2021, 37(6): 94-105.
- [8] ÖZCAN M, BERNASCONI M. Adhesion to zirconia used for dental restorations: a systematic review and meta-analysis[J]. The Journal of Adhesive Dentistry, 2015, 17(1): 7-26.
- [9] SADOWSKY S J. Has zirconia made a material difference in implant prosthodontics? A review[J]. Dental Materials, 2020, 36(1): 1-8.
- [10] Zhong J J. Preparation and properties of zirconia-based flexible ceramic fibers[D]. Wuhan: Wuhan Textile University, 2023.
- [11] Sun J W. Study on the bonding performance of self-adhesive resin cement clearfil SA luting[D]. Xi'an: The Fourth Military Medical University (now Air Force Medical University), 2011.
- [12] Xiao, N. Comparative study on the effect of polydopamine composite coating on the bond strength of zirconia ceramic[D]. Jiamusi: Jiamusi University, 2018.
- [13] SERICHETAPHONGSE P, CHITSUTHEESIRI S, CHENGPRAPAKORN W. Comparison of the shear bond strength of composite resins with zirconia and titanium using different resin cements[J]. Journal of Prosthodontic Research, 2022, 66(1): 109-116.
- [14] LIU J F, YANG C C, LUO J L, et al. Bond strength of self-adhesive resin cements to a high transparency zirconia crown and dentin[J]. Journal of Dental Sciences, 2022, 17(2): 973-983.
- [15] Wang T, Li G H. Effects of three types of adhesives on microleakage and fit of IPS e.max CAD all-ceramic crowns[J]. Beijing Journal of Stomatology, 2018, 26(3): 153-156.
- [16] Zhang Y M, Yang Q X, Wang Y, et al. Effects of resin-reinforced glass ionomer cement coating method on the cementation between dental implant abutment and zirconium crown [J]. Chinese Journal of Dental Materials and Devices, 2018, 27(2): 79-84.
- [17] Wang L, Guo X, Wei T J, et al. Effect of three kinds of resin adhesives on the adhesive strength of pure alumina[J]. Progress in Modern Biomedicine, 2018, 18(21): 4065-4068.
- [18] Li L, Xiang J Z, Ma Y L. Effect of different resin adhesives on the bond strength and edge microleakage of IPS e.max CAD all-ceramic crown [J]. Journal of Bengbu Medical College, 2020, 45(1): 78-80, 84.
- [19] Pan L P. Comparison of bond strength and marginal microleakage of different adhesives for zirconia crowns[J]. Renowned Doctor, 2022, (20): 57-59.
- [20] Zhang X Y. Effects of different sandblasting pressures on the mechanical properties and bonding strength of transparent zirconia[D]. Jinan: Shandong University, 2020.
- [21] KIM H K, YOO K W, KIM S J, et al. Phase transformations and subsurface changes in three dental zirconia grades after sandblasting with various Al<sub>2</sub>O<sub>3</sub> particle sizes[J]. Materials, 2021, 14(18):5321.
- [22] INOKOSHI M, SHIMIZUBATA M, NOZAKI K, et al. Impact of sandblasting on the flexural strength of highly translucent zirconia[J]. Journal of the Mechanical Behavior of Biomedical Materials, 2021, 115: 104268.
- [23] Li X, Su N C, Liao, Y M, et al. Effect of different conditions of sandblasting on surface loss of dental zirconia [J]. Stomatology, 2017, 37(1): 28-32.
- [24] KIM M, KIM R H, LEE S C, et al. Evaluation of tensile bond strength between self-adhesive resin cement and surface-pretreated zirconia[J]. Materials, 2022, 15(9): 3089.
- [25] LEE M H, SON J S, KIM K H, et al. Improved resin-zirconia bonding by room temperature hydrofluoric acid etching[J]. Materials, 2015, 8(3): 850-866.
- [26] Wei M, Zhu H, Liang Z R, et al. The effects of different hot acid solution etching treatment on the bonding strength and the flexural strength of zirconia [J]. Journal of Practical Stomatology, 2022, 38(4): 445-449.
- [27] SRIAMPORN T, THAMRONGANANSKUL N, BUSABOK C, et al. Dental zirconia can be etched by hydrofluoric acid[J]. Dental Materials Journal, 2014, 33(1): 79-85.
- [28] SMIELAK B, KLIMEK L. Effect of hydrofluoric acid concentration and etching duration on select surface roughness parameters for zirconia[J]. The Journal of Prosthetic Dentistry, 2015, 113(6): 596-602.
- [29] Hu Z B, Shan G H, Yang W L. Effects of surface treatment on the bond strength of transparent zirconia [J]. Chinese Journal of Prosthodontics, 2024, 25(2): 136-140.

- [30] AL-TAEE L, BANERJEE A, DEB S. In-vitro adhesive and interfacial analysis of a phosphorylated resin polyalkenoate cement bonded to dental hard tissues[J]. *Journal of Dentistry*, 2022, 118: 104050.
- [31] Lu J C, Xie H F, Zhang F M., et al. Establishment and mechanisms of chemical interaction between phosphate monomer and zirconia model [J]. *West China Journal of Stomatology*, 2017, 35(2): 145-149.
- [32] Chen Y, Xie H F, Qian M K, et al. Bonding improvement and micro-leakage evaluation of zirconia to resin via MDP conditioning [J]. *Stomatology*, 2017, 37(9): 774-777.
- [33] Liu F Xie, X F, Zhang R X, et al. Effects of 10-methacryloxy decyldihydrogen phosphate-conditioned adhesive in improving the bonding strength and marginal sealing of zirconia ceramics and resin [J]. *Chinese Journal of General Practice*, 2022, 20(6): 937-940
- [34] Zhang M Q. Effects of different surface treatments on the bond strength and durability of zirconia ceramic and resin cement[D]. Changchun: Jilin University, 2023.
- [35] ALTAN B, CINAR S, TUNCELLI B. Evaluation of shear bond strength of zirconia-based monolithic CAD-CAM materials to resin cement after different surface treatments[J]. *Nigerian Journal of Clinical Practice*, 2019, 22(11): 1475-1482.
- [36] DE FIGUEIREDO V M G, SILVA A M, MASSI M, et al. Effect of the nanofilm-coated zirconia ceramic on resin cement bond strength[J]. *Journal of Dental Research, Dental Clinics, Dental Prospects*, 2022, 16(2): 170-178.
- [37] CHEUNG G J, BOTELHO M G. Zirconia surface treatments for resin bonding[J]. *The Journal of Adhesive Dentistry*, 2015, 17(6): 551-558.
- [38] SAADE J, SKIENHE H, OUNSI H F, et al. Evaluation of the effect of different surface treatments, aging and enzymatic degradation on zirconia-resin micro-shear bond strength[J]. *Clinical, Cosmetic and Investigational Dentistry*, 2020, 12: 1-8.
- [39] Lu Z, Qin S, Liu H. Research progress on the application of low-temperature plasma in stomatology[J]. *Chinese Journal of Geriatric Dentistry*, 2019, 17(5): 304-307, 318.
- [40] Jiang Y L. Effects of different plasma treatments on the bonding performance of zirconia[D]. Dalian: Dalian Medical University, 2022.
- [41] LIU T, HONG L, HOTTEL T, et al. Non-thermal plasma enhanced bonding of resin cement to zirconia ceramic[J]. *Clinical Plasma Medicine*, 2016, 4(2): 50-55.
- [42] VALVERDE G B, COELHO P G, JANAL M N, et al. Surface characterisation and bonding of Y-TZP following non-thermal plasma treatment[J]. *Journal of Dentistry*, 2013, 41(1): 51-59.
- [43] PARANHOS M P, BURNETT L H Jr, MAGNE P. Effect of Nd:YAG laser and CO<sub>2</sub> laser treatment on the resin bond strength to zirconia ceramic[J]. *Quintessence International*, 2011, 42(1): 79-89.
- [44] LIU L, LIU S, SONG X, et al. Effect of Nd:YAG laser irradiation on surface properties and bond strength of zirconia ceramics[J]. *Lasers in Medical Science*, 2015, 30(2): 627-634.
- [45] TZANAKAKIS E G, DIMITRIADI M, TZOUTZAS I, et al. Effect of water storage on hardness and interfacial strength of resin composite luting agents bonded to surface-treated monolithic zirconia[J]. *Dentistry Journal*, 2021, 9(7): 78.
- [46] Du Q, Niu G. Effect of laser and coating surface treatment on the bond strength of zirconia ceramics [J]. *West China Journal of Stomatology*, 2024, 42(3): 359-364.
- [47] ESTEVES-OLIVEIRA M, JANSEN P, WEHNER M, et al. Surface characterization and short-term adhesion to zirconia after ultra-short pulsed laser irradiation[J]. *The journal of adhesive dentistry*, 2016, 18(5): 483-492
- [48] YILMAZ-SAVAS T, DEMIR N, OZTURK A N, et al. Effect of different surface treatments on the bond strength of lithium disilicate ceramic to the zirconia core[J]. *Photomedicine and Laser Surgery*, 2016, 34(6): 236-243.
- [49] VICENTE PRIETO M, GOMES A L C, MONTERO MARTÍN J, et al. The effect of femtosecond laser treatment on the effectiveness of resin-zirconia adhesive: an in vitro study[J]. *Journal of Lasers in Medical Sciences*, 2016, 7(4): 214-219.
- [50] YE Q, ZHOU F, LIU W. Bioinspired catecholic chemistry for surface modification[J]. *Chemical Society Reviews*, 2011, 40(7): 4244-4258.

- [51] Mulyati S, Muchtar S, Arahman N, et al. Two-step dopamine-to-polydopamine modification of polyethersulfone ultrafiltration membrane for enhancing anti-fouling and ultraviolet resistant properties[J]. *Polymers*, 2020, 12(9):2051.
- [52] Liu Y H, Liu D, Wang Y, et al. Research progress of the surface modification by dopamine in medical field[J]. *Surface Technology*, 2022, 51(11): 164-173.
- [53] Xiao N, Hou Y Z, Hou Y. Effect of polydopamine on the shear bond strength of zirconia ceramic [J]. *Beijing Journal of Stomatology*, 2018, 26(6): 323-326.
- [54] Wang X F. Fundamental study on the effect of bonding surface coating on the bond strength of zirconia ceramics[D]. Nanjing: Nanjing Medical University, 2011.
- [55] Li B C. Research on polydopamine functional coatings and nanoparticles for biomedical applications[D]. Hangzhou: Zhejiang University, 2018
- [56] Lee S B, González-Cabezas C, Kim K M, et al. Catechol-functionalized synthetic polymer as a dental adhesive to contaminated dentin surface for a composite restoration[J]. *Biomacromolecules*, 2015, 16(8): 2265-2275.
- [57] Lee H A, Park E, Le H. Polydopamine and its derivative surface chemistry in material science: a focused review for studies at KAIST[J]. *Advanced Materials*, 2020, 32(35): e1907505.
- [58] Krosgaard M, Nue V, Birkedal H. Mussel-inspired materials: self-healing through coordination chemistry[J]. *Chemistry*, 2016, 22(3): 844-857.
- [59] Li M, Hua C G, Jiang L. Research progress on new technology for improving adhesion properties of zirconia ceramics [J]. *International Journal of Stomatology*, 2021, 48(4): 485-490.
- [60] Ali N, Safwat A, Aboushelib M. The effect of fusion sputtering surface treatment on microshear bond strength of zirconia and MDP-containing resin cement[J]. *Dental Materials*, 2019, 35(6): e107-e112.
- [61] Oğuz E, Özgür M E, Sungur S, et al. Impact of multiple firings and resin cement type on shear bond strength between zirconia and resin cements[J]. *The Journal of Advanced Prosthodontics*, 2020, 12(4): 197-203.
- [62] Yin L, Cheng Q H, Chen Z, et al. Study on the influence of 3D printing zirconia patterned design and surface pretreatment methods on adhesive performance [J]. *Chinese Journal of Practical Stomatology*, 2024, 17(6): 684-690.
- [63] Zhang J, Zhang Y, Lv X, et al. The effect of air abrasion on dentin-resin adhesive system [J]. *Journal of Practical Stomatology*, 2004, 20(4): 472-474.
- [64] Ma H W, Wang J H, Liu Z J. Research progress on filling treatment of wedge-shaped defects [J]. *Stomatology*, 2018, 38(3): 285-288.
- [65] Jiang B L, Huang C. Influence of different etching modes on bonding effects of universal adhesives[J]. *Journal of Oral Science Research*, 2022, 38(11): 1018-1021.
- [66] Alrahlah A, Niaz M O, Abrar E, et al. Treatment of caries affected dentin with different photosensitizers and its effect on adhesive bond integrity to resin composite[J]. *Photodiagnosis and Photodynamic Therapy*, 2020, 31: 101865.
- [67] Yang C, Miao Y. Analysis of adhesive performance of different types of dental restorations[J]. *Inner Mongolia Medical Journal*, 2024, 56(2): 205-208.
- [68] Liber-Kneć A, Łagan S. Surface testing of dental biomaterials-determination of contact angle and surface free energy[J]. *Materials (Basel, Switzerland)*, 2021, 14(11):2716.
- [69] Jokstad A, Bayne S, Blunck U, et al. Quality of dental restorations: FDI Commission Project 2-95[J]. *International Dental Journal*, 2001, 51(3): 117-158.
- [70] Zhu G R S, Tian Y M, Zhang Z T, et al. Effect of subpressure technique on total-etching dentin bonding [J]. *Beijing Journal of Stomatology*, 2017, 25(1): 11-14.
- [71] Wang H M, Zhu Y L, Yang Y B, et al. Research progress in the effect of EDTA pretreatment of dentin on self-etching bonding [J]. *Chinese Journal of Practical Stomatology*, 2021, 14(3): 370-373.
- [72] Alcántara-Obispo E, Santander-Rengifo F, Ladera-Castañeda M, et al. Adhesive strength in dentin conditioned with 18% ethylenediaminetetraacetic acid versus 35% phosphoric acid: in vitro study with 1-year artificial aging[J]. *Polymers*, 2022, 14(20): 1234.

- [73]Zhang Y, Huang Y, Pang Y Y, et al. Biomimetic remineralization of infected demineralized dentin using procyanidins to simulate the biological function of glycosaminoglycans[C]//Proceedings of the 14th National Academic Conference on Dental Caries and Endodontics. Tianjin: Tianjin Medical University Stomatological Hospital, 2022: 159-161.