



REVIEW ARTICLE

METAL SURFACE TREATMENTS AND THEIR EFFECT ON METAL-CERAMIC BOND STRENGTH: A REVIEW

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Abstract. Despite the popularity of metal-ceramic restorations, bonding issues exist between metal and ceramic materials. Ceramic fractures in metal-ceramic restorations present significant aesthetic and functional challenges for both patients and dentists. Ceramic-fused-to-metal restorations are being developed to enhance the resistance to fracture of dental ceramic. A variety of metal alloys surface modifications, encompassing various physical, chemical, and biological techniques, have been implemented on a broad spectrum of precious and non-precious metal alloys, including Cobalt-Chromium (Co–Cr), Palladium-Silver (Pd-Ag), and Nickel-Chromium (Ni–Cr). These surface treatments strengthen the ceramic bond strength on metal alloys. In this review, we provide deep insights about various metal-ceramic alloys and the surface treatments utilized to enhance effectiveness in dental restorations. This study, for the first time, reviewed multiple studies evaluating the effectiveness of various surface metal treatments on their metal-ceramic bond strength. Pertaining to literature, it is evident that surface treatments like sandblasting, acid etching, and grinding improved the metal alloys' bond strength. Scanning electron microscope (SEM) results demonstrated a markedly roughened metal surface following treatment, which is crucial for interaction in between metal and ceramic in enhancing bond strength. Most of the research has focused on the surface treatment's effectiveness on the metal-ceramic bond in nonprecious or base metal alloys, whereas investigations involving noble or precious metals are limited. Nonetheless, these results primarily originate from preclinical studies and necessitate subsequent validation within the complex oral environment.

Keywords: Metal-ceramic alloys, bond strength, scanning electron microscope, surface treatment.

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1. INTRODUCTION

Despite numerous studies aimed at advancing ceramic systems, metal-ceramic fixed prostheses remain crucial due to the range of uses and cost-effectiveness in comparison to ceramic fixed prostheses. Metal-ceramic prosthetic restorations have been applied to clinical practice for decades, with studies demonstrating survival rates as high as 90% over a duration of 10–15 years, attributed to their biocompatibility as well as aesthetics, being considered larger than alternative options [1]. A decade later, metal-ceramic crowns (88.7%) & fixed partial dentures (80.2%) remained functional, based on the longitudinal studies [2]. Metal-ceramic restoration of the ceramic part may perform substantial functions; however, the overall success of the prosthesis is primarily dependent upon the physical characteristics of the metal substructure [3]. The strength of these types of restorations serves as a crucial determinant for its longevity in the variable oral environment (pH, chemical modifications, temperature variations) as well as underneath the influence of substantial and variable forces. Consequently, selecting the suitable material and fabrication technique for metal-ceramic restorations is a critical factor in safeguarding them against fracture [4].

Metal possesses superior mechanical strength compared to ceramic, thereby enhancing the fracture resistance of the restoration [5]. The efficacy of metal-ceramic prostheses is mainly dependent upon the optimal bond strength between their corresponding metal in addition to ceramic parts. Despite being popular, bonding concerns regarding metal-ceramic restorations exist between the metal and ceramic components. The detachment of the ceramic surface from its metallic part results in an adverse outcome for both patients and dentists [6]. Pre-treatment of metal surfaces prior to applying ceramic enhances bonding strength, connecting the ceramic and metal. Nonetheless, consensus on the optimal technique for metal preparation for ceramic bonding remains elusive.

Numerous treatment methods for the metal substrate earlier to porcelain fabrication had been suggested, including: double and vacuum oxidation; specification-based oxidation; specification-based oxidation/sandblasting; and sandblasting [7]. While it has been found that surface treatment techniques affect the bond strength of porcelain metals, limited literature correlates bond strength values with various surface treatment types [7,8].

Multitude of studies aimed at comparing various surface treatments and their effectiveness on bond strengths across various metals and ceramics. Nonetheless, views regarding the precise preparation of metals during ceramic bonding remain inconsistent. This review aims to present comprehensive insights into the different kinds of metal surface treatments being applied in restorative dentistry and their effect on metal-ceramic bond strength across various metals and ceramics.

2. TYPES OF METAL-CERAMICS ALLOYS

2.1 Noble-metal metal-ceramic alloys

Gold–platinum–palladium (Au–Pt–Pd) alloys are initial materials utilized effectively for metal-ceramic restorations. Nevertheless, their application reduced following the development of more cost-effective alloys exhibiting notably superior mechanical properties and sag resistance. Due to their insufficient sag resistance, these alloys only affected crowns & three-unit fitted partial dentures [9]. To address the shortcomings of Au–Pt–Pd alloys, Gold–Palladium–Silver (Au–Pd–Ag) alloys were created. Au–Pd–Ag alloys posed better costs, increased hardness, and wear resistance. Our main concern with these alloys is that their silver concentration may discolor porcelain [10]. Substantially, gold-palladium (Au–Pd) alloys were later on came up to solve the principal challenges linked with Ag-comprising alloys [9]. Lower silver content inhibits porcelain discoloration, improves castability, and elevates the thermal expansion coefficient [11]. Table 1 presents different metal-ceramic alloys' properties.

Table 1: Characteristics of various base as well as noble metal-ceramic alloys

Metal alloy	Casting temp. (°C)	Tensile strength (MPa)	Elastic modulus (GPa)
Pd–Ag	1310–1350	550–730	95–117
Au–Pd–Ag	1320–1350	650–680	100–113
Pd–Cu	1170–1190	690–1300	94–97
Au–Pd	1320–1330	700–730	100–117
Co–Cr	1350–1450	520–820	145–220
Au–Pt–Pd	1150	480–500	81–96
Ni–Cr	1300–1450	400–1000	150–210

In 1974, palladium-silver (Pd-Ag) alloys came in, serving as a cheaper substitute for pricier Au-containing alloys. With superior sag resistance as well as adequate bond strength of porcelain, Pd–Ag alloys have the best noble-metal metal-ceramic elastic modulus. However, certain Pd–Ag alloys result in greater porcelain discoloration compared to Au–Pd–Ag alloys. Silver alloys may be subjected to staining by evaporating as a (+)-charged ion at some stage in the firing of porcelain [12]. In the later part of the 1980s, various high-palladium alloys were introduced. Despite being popular during the 1990s, the price volatility of Pd gave rise to the development of newer alloys. Incorporation of copper and indium in palladium-copper (Pd-Cu) alloys reduces gallium's solid solubility, resulting in eutectic reaction on smaller gallium wt. (%). This is believed to offer superior hardening and strengthening due to the increased formation of the eutectic constituent [13]. High yield strength and hardness were the Pd-Cu alloy's main disadvantages, which hinder finishing & polishing during fabrication.

Palladium-cobalt (Pd-Co) represents another category of high-palladium alloys. Their primary advantage is a comparatively elevated coefficient of thermal expansion, beneficial for specific porcelain systems [11]. Additionally, the Pd–Cobalt alloy's porcelain bond strength is lower. In addition, the introduced palladium-gallium (Pd-Ga) alloys generated oxide layers that exhibit inferior ceramic bonding capabilities compared to the palladium-copper (Pd-Cu) alloys. Following the discovery of the limitations in Pd-Cu as well as Pd-Co alloys, Pd-Ag-Au alloys garnered interest [9]. High-temperature strength along with decreased surface oxide layer distinguish Pd–Ag–Au alloys from various high Pd-containing alloys.

2.2 Base-metal metal-ceramics alloys

Figure 1 observes classification of various metal-ceramic alloys. Nickel (Ni) and cobalt (Co) are the two most common metal-ceramic alloys. In the first two systems, alloys have chromium as their second most significant component, relying on it for resistance to corrosion. Despite the longstanding prevalence of Ni- and Co-based alloys, many researchers continue to investigate alternative metal-ceramic alloys using base-metal due to their enhanced physical properties, particularly titanium (Ti) [13].

All nickel-chromium (Ni-Cr) alloys share similar compositions as well as physical properties yet vary in their resistance to corrosion [14]. Elements such as iron, tungsten, vanadium, and molybdenum are incorporated into Ni-Cr alloys to enhance hardening and exhibit greater efficacy. Cobalt serves as the principal constituent in Co-Cr alloys, increasing strength while adding corrosion resistance. Co-Cr alloys are further categorized in two subcategories: ones including ruthenium (Ru) and ones lacking Ru. Co-Cr alloys serve as the primary base-metal alternative for individuals with documented nickel allergies [14].

Titanium is regarded as most biocompatible metal in dental prostheses. The titanium–aluminium–vanadium (Ti–6Al–4V) alloys are largely prevalent Ti alloys utilized in dental as well as medical applications. Titanium alloys possess elevated melting points (approximately 1600°C), and casting is frequently conducted using specialized induction casting techniques in an argon atmosphere [15]. Controlling high-temperature titanium oxidation as well as adjusting titanium's reduced thermal expansion improved ceramic bonding. Furthermore, a bonding agent containing titanium particles markedly enhanced porcelain's adhesion to a machined Ti surface.

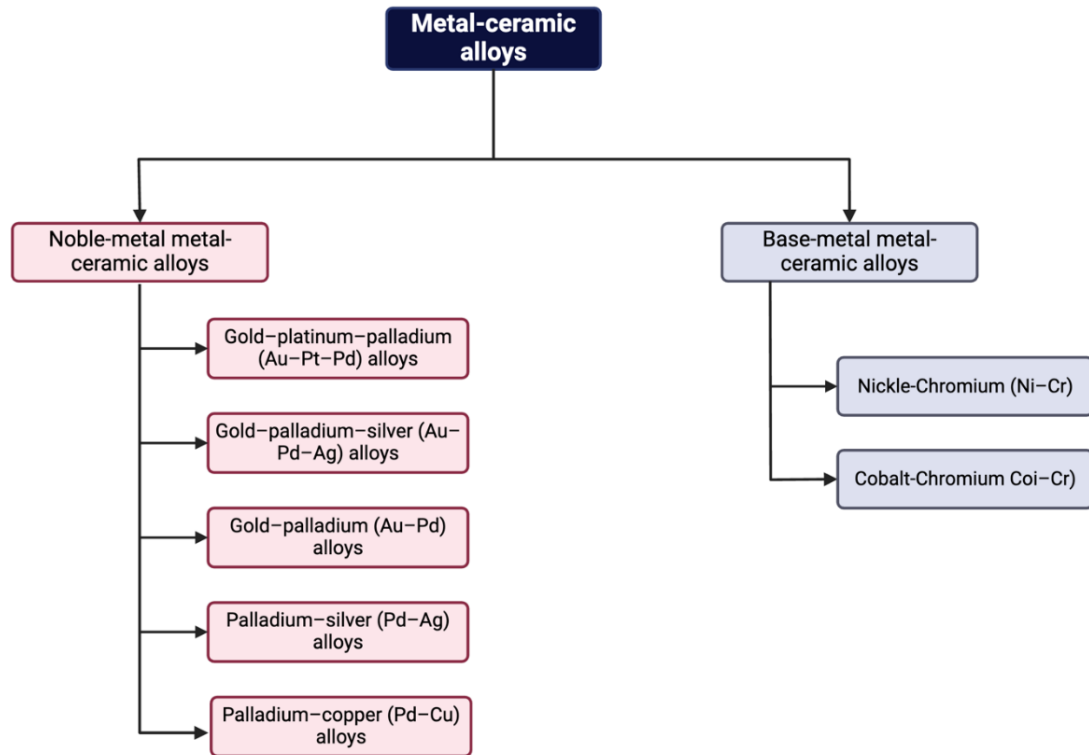


Figure 1: Classification of various metal-ceramic alloys. Created using BioRender

3. TYPES OF METAL-SURFACE TREATMENTS

The development of restorative prostheses and their surfaces has consistently evolved to enhance metal-ceramic bonding and improve long-term survival rates. Surface treatments modify the microstructure of metal alloys by altering roughness, creating micro-pits, and enhancing oxide layer formation, which improves mechanical interlocking and chemical adhesion. There are three distinct categories of methods for modifying metal surfaces during manufacturing: Mechanical treatments such as grinding, blasting, air abrasion with aluminium oxide, and gritting; chemical treatments including acid etching and saline coupling; physical treatments comprising sandblasting and grit blasting [16]. The subsequent sections describe different metal surface treatments. Figure 2 illustrates different metal surface treatment types for restorative prosthesis.

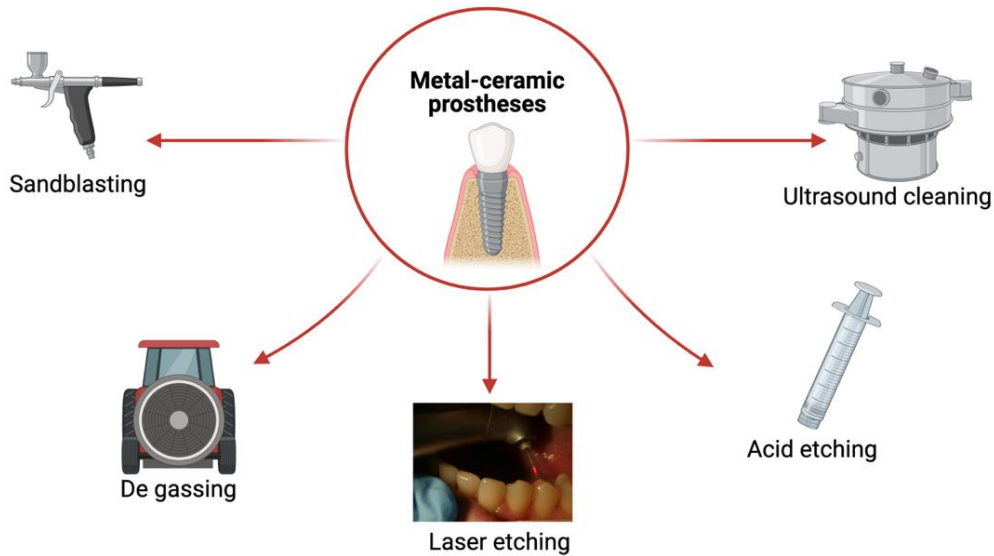


Figure 2: Different types of metal surface treatments. Created using BioRender

3.1. Sandblasting

This is a mechanical method that employs high-speed abrasive particles to cleanse, strengthen, and polish metallic surfaces. It readies the metal surfaces for subsequent treatments such as coating. It includes using compressed air to blow abrasive particles through a blasting nozzle. Repeated particle impact causes surface irregularities. These micro-irregularities increase mechanical strength. The samples are typically subjected to sandblasting (0.3 MPa) on to the terminal surfaces of the test sample using 110–50 μm aluminium oxide (Al_2O_3) particles in a sandblasting system for a duration of 10-20 seconds [17]. Grit blasting must always be accompanied by acid etching.

3.2. Acid Etching

Acid etching is a chemical process that causes surface erosion on a hard material, such as metal, through the application of a specifically formulated etching acid (etchant). This technique employs acids on the metal surface not solely for cleaning but also for roughening the surface. Nitric acid, hydrofluoric acid, as well as sulfuric acid are amongst various acids utilized in treating through the acid etch technique. Research indicates that acid-etched treated surfaces of implants demonstrate superior bonding with metal surfaces, resulting in enhanced bonding strength. The etching rate is entirely depending upon the concentration of the acid employed. It is a straightforward, less technique-sensitive, and economical method for surface treatment [18].

3.3. Surface Grinding

Surface grinding is a machining technique employed to attain smooth and uniform surfaces on a metallic workpiece. Surface grinding induces micro-locking between ceramics and metal, enhancing mechanical retention. Abrasive materials frequently utilized for grinding wheel comprise Al_2O_3 , silicon carbide, diamond, as well as cubic boron nitride. It is typically accompanied with the sandblasting process. Surface grinding facilitates accurate cuts and rapid metal removal. The test specimens are typically exposed to surface grinding at surface end wherein the ceramic is affixed, via 0.5 mm diameter carbide bur (DFS) to perform unidirectional grinding [16]. Surface grinding induces micro-locking amongst porcelain and metal, thereby enhancing mechanical endurance.

3.4. Degassing

Degassing, often termed oxidation, outgassing, and pre-oxidation, eliminates gases absorbed during casting and inhibits the formation of interfacial bubbles. It generates a metal oxide layer binding metal and porcelain chemically [16]. Degassing transpires during the initial heat cycle, or oxidation cycle, in the fabrication of a metal-ceramic restoration. It is conducted under diminished pressure to eliminate the gases. The process generally entails positioning the samples in a Dentsply ceramic furnace, raising the temperature to 1950°F (1065°C), and sustaining underneath a 28-inch mercury (Hg) vacuum over five minutes. Degassing is performed as the final step to avoid disturbing the oxide layer.

3.5. Ultrasonic Cleaning

Ultrasonic cleaning systems can efficiently and thoroughly cleanse metal surfaces. Although alternative cleaning methods like chemical or mechanical cleaning may also be employed, ultrasonic cleaning is more expedient and eliminates the need for chemical solvents, rendering it more environmentally sustainable [19]. Ultrasonic cleaning employs alternating compression and rarefaction cycles to generate cavitation, effectively eliminating contaminants via vibrations. Ultrasonic cleaning offers advantages such as the ability to clean inaccessible areas of metal, gentleness on fragile welded joints and small components, and increased speed compared to traditional methods.

3.6. Laser Etching

Lasers have primarily been utilized for the surface modification of implant metals. Neodymium-doped Yttrium Aluminium Garnet lasers, CO₂ lasers, Nd:YVO₄ lasers, Yb:KGW lasers, Yb:KYW lasers, Yb:YAG lasers, and femtosecond lasers are utilized for the modification of metal surfaces. Laser light facilitates oxygen diffusion in molten metal, oxidizing the surface and creating different morphologies. The concept of laser etching is to remove particles via a process called ablation, which generates micro-porosities and improves micromechanical retention. This procedure entails micro-explosion and vaporization [20]. For example, using an Er:YAG laser, a dental handpiece (R14-C) is used along with a fiber-optic tip, setting the pressure to two bars for both water and air. Etching done moving from bottom to top, the tip was kept in minimal contact with metal surface with the parameters: 500mJ of energy level, 100 μs of pulse width, and 10 Hz of frequency for 45 seconds. Laser treatments and plasma-based modifications demonstrate superior performance compared to conventional methods by offering enhanced control over surface roughness, facilitating improved oxide layer formation, and increasing wettability, which results in greater bond strength and long-term durability.

3.7. Grinding Bur

Dental grinding burs are rotary instruments utilized for grinding, cutting, and polishing hard tissues. This is carried out to enhance surface quality and increase the surface bonding area. Typically, metal composites are abraded using a diamond fissure bur (100 μm) and a rotating handpiece (45,000 rpm) with continuous water irrigation for 8 seconds [21].

4. APPLICATIONS OF SCANNING ELECTRON MICROSCOPY (SEM)

The discipline of dental prosthetics has pioneered various innovative technologies and techniques that enable the production of precise, customized, optimal dental restorations. Among current Computer-Aided systems with extensive applications in this domain, the most prevalent include Rapid Prototyping, Computer-Aided Design, as well as 3D digitization systems. Precision, fracture resistance, along with aesthetics determine fixed dental restoration quality. Moreover, morphological discrepancies and defects between the crown and the tooth, along with variations in their marginal contours, typically lead to unacceptable marginal-gaps [22]. SEM remain as one of the precise

techniques frequently employed to assess the precision of fixed dental restorations (Figure 3) [23]. Moreover, its application does not result in the destruction of the sample.

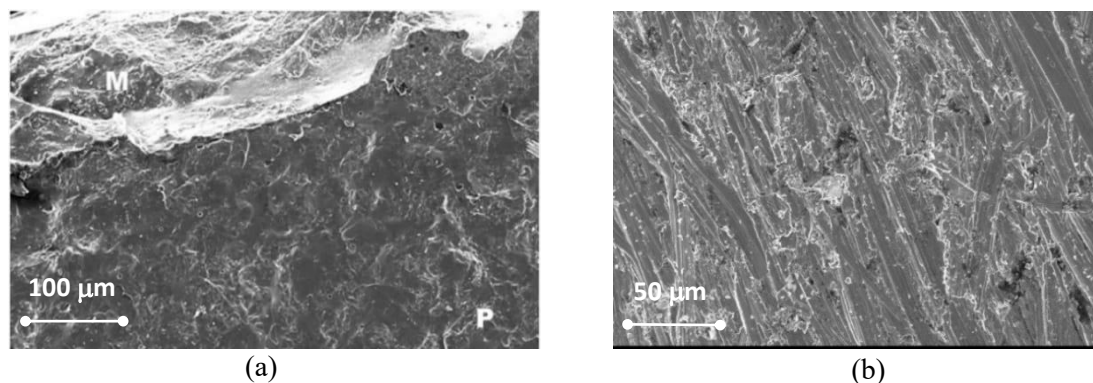


Figure 3: SEM images depicting (a) surface micro-irregularities following the surface treatment and (b) Debonded surface. Indicating P as porcelain and M as metal. Adapted from Belkhode et al. [16]

The achievement of smooth surfaces in dental restorations is crucial for oral health and aesthetic requirements. In dental restorations, teeth's surface roughness (SR) as well as plaque accumulation, restoration coloration, and aesthetics, are directly correlated. Furthermore, it has been determined that the reduction of surface roughness diminishes friction, subsequently decreasing wear and potentially enhancing clinical performance. SR assessments can be carried out utilizing qualitative techniques, including SEM [24]. SEM operates on the principle where a diminutive (10 µm) electron beam moves from one point to yet another across the surface being analyzed. SEM is a commonly employed technique for examining surfaces exhibiting scratches and distortions. Nonetheless, it possesses certain limitations in defining surface topography as well as the 3D surface characteristics which could not be displayed [25].

5. EFFECT OF SURFACE TREATMENT ON METAL-CERAMIC BOND

5.1. Effect on Base Metal Alloys

Dental restorations using metal-ceramic alloys are being widely employed for several decades already. Ceramic restorations featuring metal substructures provide the porcelains' aesthetic appeal combined along with its metal components' durability. Adhering porcelain to metal enhances its strength through a metallic substructure. The attributes of high strength, minimal bulk, low thermal conductivity, and fusion characteristics render non-precious metal alloys optimal for porcelain subcomponents [26]. The effectiveness of metal-ceramic restorations is based on their mutual bond, being governed using weak van der Waals forces, chemical bonding, compressive forces, as well as mechanical interlacing resulting from the thermal expansion coefficient. Surface modifications improve these mechanisms by increasing surface roughness to enhance mechanical retention, optimizing oxide layer formation to strengthen chemical adhesion, and improving wettability to enhance van der Waals interactions. Table 2 illustrates various studies using different surface treatments to evaluate metal-ceramic bond strength.

A different study assessed the bond strength of non-precious alloy following seven distinct surface treatments. The SR of the alloy that demonstrated the greatest bond strength was sandblasting, succeeded by surface grinding, a second application of sandblasting, and degassing. The alloy surface treatment, which included supplementary steam cleaning post-sandblasting, demonstrated the lowest bond strength [27]. This was likely caused by ultrasonic cleaner air bubbles and contaminants becoming trapped in surface irregularities [16]. Consequently, the literature clearly indicates that the degassing process enhanced bond strength, whereas wet steaming the surface diminished it. Shear bond strength and three-point bending are the most reliable bond strength tests, as they directly evaluate adhesive performance under stress and reveal interfacial integrity and flexural resistance.

Further research is essential to enhance understanding of bond strength using the characteristics of bond failing, utilizing a greater sample size along with additional advanced tools. Moreover, additional research is necessary to evaluate SR utilizing sophisticated instruments like confocal laser scanning microscopy, three-dimensional scanning microscopy, as well as profilometry for improved assessment. In addition, validating preclinical study outcomes in the intricate oral environment is crucial to consider factors such as saliva, temperature variations, mechanical stresses, and microbial activity, all of which can substantially influence material performance and durability.

Table 2: Various studies evaluating metal-ceramic bond strength using different surface treatments

Reference	Metal Alloy	Surface Treatments	Findings
Belkhode et al. [16]	Co–Cr	Sandblasting, surface grinding, ultrasonic cleaning, degassing	The combination of sandblasting, surface grinding, as well as ultrasonic cleaning, succeeded by degassing, produced the highest tensile-bond strength.
Gourav et al. [17]	Ni–Cr	Sandblasting, etching, grinding bur	Treated exposed metal surfaces can enhance shear bond strength.
Lahori et al. [27]	Ni–Cr	Sandblasting, grinding, degassing, steam cleaning	Degassing the alloy before applying porcelain improved bond strength.
Asproudi et al. [7]	Ni–Cr & Co–Cr	Oxidation, sandblasting	The metal–ceramic bond is strongest when the metal substrate is specified oxidized.
Elkallaf et al. [20]	Ni–Cr & Co–Cr	Sandblasting, metal conditioner, laser etching	Sandblasting provided highest bond strength compared to all surface treatment methods.
Khmaj et al. [28]	Aquarius (Au; Pd; Indium) Hard, Evolution (Au; Pd; Ag; In; Gallium) Lite, Callisto 75 Pd (Pd; Ag; Au; In; Tin), Aries (Pd; Ag; Tin; Gallium; In)	Press-on-metal, conventional layering	Both conventional layering and press-on-metal techniques increased metal-to-ceramic bond strength of all four noble alloys.

5.2. Effect on Noble/Precious Metal Alloys

Since their introduction in 1970s, Pa–Ag alloys proved their appropriateness in dentistry. They were explicitly designed as cost-effective substitutes for pricier Au-based alloys. Pa–Ag alloys are more biocompatible than other non-precious metals. In addition, comparably, Pd–Ag alloys remain distinctive due to their capacity to dissolve significant quantities of oxygen at elevated temperatures, resulting in internal oxidation [29]. The metallic internal oxidation claim that oxygen enters the Pd–Ag alloy and further has reaction with the tin (Sn) as well as indium (In). A study discovered that metallic Pd–Ag nodules on the Pd–Ag–Sn–In alloy following pre-porcelainizing oxidation at temperatures exceeding 750 °C, in the absence of an oxide film [30]. The relationship between the quantity of metallic nodules and MC bond strength has not been investigated. Moreover, abrading the metal alloys’ surface using Al₂O₃ enhances mechanical interlacing and expands the metals’ surface-area in contact with the

coated ceramic. Thus, heat treatment along with air-particle abrasion have proven highly effective in improving bond strength over the metal-ceramic interface. Khmaj et al. [28] examined the bond strength of various noble metal alloys for porcelain applications utilizing two methodologies: conventional layering and press-on-metal techniques. The findings indicated that both methods enhanced the average ceramic bond strength across all noble metals.

Furthermore, key bonding issues in metal-ceramic restorations include insufficient oxide layer formation, discrepancies in thermal expansion, residual stresses, and interfacial defects like porosity or microcracks, all of which may result in bond failure and delamination. Studies indicate that the combination of sandblasting, surface grinding, and ultrasonic cleaning, followed by degassing, resulted in the highest tensile-bond strength [16]. Surface treatments on non-precious metal alloys primarily improve oxide layer formation and mechanical interlocking, whereas treatments on precious metal alloys aim to enhance wettability and micromechanical retention due to their reduced natural oxide reactivity. Moreover, surface roughness of metals enhances bond strength through improved mechanical interlocking, increased surface area for adhesion, and the promotion of uniform oxide layer formation, all of which jointly strengthen the metal-ceramic interaction.

6. CONCLUSIONS

This review article reviewed various metal-ceramic alloys, and the surface treatments employed to improve their efficacy in dental restorations. This study, for the first time, reviewed various investigations into the impact of various surface treatments onto metal-ceramic bond strength. Furthermore, the advantages and disadvantages of each method were examined. This study concludes that surface treatments strengthen metal-ceramic bonding. SEM results indicated a significantly roughened metal surface post-treatment, required for mechanical interaction in between metal and ceramic, improving bond strength. Due to their cost-effectiveness and superior strength properties, most studies have examined the impact of surface treatments on the metal-ceramic bond in nonprecious or base metal alloys. The impact of surface treatments on noble metal alloys is under-researched, with limited studies examining the influence of heat treatment. Sandblasting, followed by acid etching and grinding, enhanced the bond strength. Degassing the alloy prior to porcelain application enhanced bond strength, whereas wet cleaning diminished it. Nonetheless, these findings are predominantly *in vitro* and require validation within the intricate oral environment. Diverse factors, including pH alterations, bacterial composition, variations in temperature, and masticatory pressure in the oral cavity, can affect the results. Therefore, the study's findings require validation through clinical studies.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare

Compliance with Ethical Standards

The work is compliant with ethical standards.

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