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Shear Bond Strength and Surface Roughness of Titanium Dental Alloys Fabricated by Using Different Techniques Bonded to Two Different Veneering Materials: A Narrative Review

Mohamed T. Elboghdady[1*], M. A. Eldemellawy[2], Ingy Mohamed Hany Nouh[3]

[1]Master Student, Fixed Prosthodontics Department, Faculty of Dentistry, Ain Shams University, Cairo, Egypt

[2]Professor of Fixed Prosthodontics, Faculty of Dentistry, Ain Shams University, Cairo, Egypt

[3]Associate Professor of Fixed Prosthodontics, Faculty of Dentistry, Ain Shams University, Cairo, Egypt

Abstract

Titanium and its alloys have become increasingly prevalent in prosthetic dentistry due to their exceptional biocompatibility, corrosion resistance, and favorable mechanical properties. However, achieving a durable bond between titanium frameworks and veneering materials remains a significant clinical challenge. This narrative review synthesizes current evidence on the influence of fabrication techniques -conventional casting, computer numerical control (CNC) milling, and selective laser melting (SLM)- on the bond strength and failure characteristics of titanium-veneered assemblies. The adhesion strength between porcelain coating and metal infrastructure in metal-ceramic fixed dental prostheses is essential for their durability. The review examines the inherent challenges of titanium-ceramic bonding, including excessive oxide layer formation, coefficient of thermal expansion mismatch, and processing difficulties associated with titanium's high melting temperature and reactivity. The transition from conventional casting to subtractive and additive CAD/CAM technologies has provided alternative processing routes that may influence surface characteristics and bond integrity. The evidence indicates that fabrication technique significantly influences failure mode distribution, with casting predominantly associated with adhesive failure, while CNC milling and SLM demonstrate a higher prevalence of mixed failure, suggesting superior bond characteristics. Veneering material selection -low-fusing porcelain versus composite resin- does not appear to significantly influence failure mode distribution, providing clinicians with greater material flexibility. The review also examines surface conditioning methods and their role in enhancing titanium-veneer adhesion. The findings support the adoption of SLM technology for titanium frameworks in high-load prosthetic applications and emphasize the importance of standardized surface preparation protocols for optimizing clinical outcomes.

Keywords: Titanium alloys, Ti-6Al-4V, surface roughness, shear bond strength, selective laser melting, CNC milling, casting, failure mode analysis, dental prosthesis, metal-ceramic bonding

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1. Introduction

Complex full-mouth reconstructions and full-arch implant rehabilitations have imposed high demands on framework materials and their veneering systems. While the veneering layer must replicate tooth shape and optical characteristics, withstand wear and fracture, and remain chemically or adhesively linked to the framework under cyclic mechanical and thermal loads, the substructure must be rigid, corrosion-resistant, and biocompatible [1-2]. Since the 1960s, metal-ceramic restorations have been utilized to combine the superior aesthetic qualities of ceramic with the high resilience of metal, and they remain the fundamental basis of contemporary prosthetic dentistry for rehabilitation. The long-term success and durability of these prostheses depend critically on the strong bond established at the metal-veneer interface [3-4]. Historically, high-noble and base metal alloys (e.g., Ni-Cr, Co-Cr) have been widely used in this field. However, increasing clinical and regulatory demands for biocompatibility, alongside rising material costs, have driven implementation of alternative materials [5-6]. Prosthodontics and implantology have observed a rise in the use of titanium (Ti) and its alloys, especially commercially pure titanium (CP Ti, usually Grades 2 and 4) and the alpha-beta alloy Ti-6Al-4V (Grade 5).

Titanium is widely valued because of its outstanding biocompatibility, high corrosion resistance, favorable mechanical qualities, high strength-to-weight ratio, and comparatively low cost [7-9]. Furthermore, Ti-6Al-4V is frequently chosen for high-occlusal-load applications due to its improved mechanical strength properties [10-11]. Despite

these beneficial characteristics, obtaining a strong bond between titanium frameworks and veneering materials remains a significant clinical and laboratory issue [12-13]. The degree of adhesion between the metal substructure and the veneering material is a major factor in the long-term performance of metal-veneered restorations. Function and appearance may be compromised by inadequate bonding, which can lead to veneer fracture, delamination, chipping, or total restoration failure, which may necessitate repair or remake and maintenance costs in high-load full-arch scenarios [14-15]. The high melting temperature and reactivity of titanium cause problems in the production of prosthetic constructions by casting [16]. That is why there is a tendency to move to modern CAD/CAM technologies—milling and selective laser melting (SLM) [17]. On the other hand, the implementation of CAD/CAM technologies in dental laboratories is a prerequisite for the increased interest in application of titanium and its alloys for production of metal-ceramic fixed dental prostheses [18].

Selective laser melting (SLM) has become an important part of digital dental workflows, allowing for the direct creation of dental frameworks from computer-aided design (CAD), offering advantages over traditional casting and subtractive milling techniques [19-20]. Alloys based on titanium produced through SLM exhibit strong mechanical properties, fatigue resistance, and biological compatibility when suitable post-processing is conducted [21]. Recent advances in subtractive and additive CAD/CAM technologies have provided alternative routes for titanium processing. The effect of a processing route on titanium surface characteristics and on the strength of its bond to porcelain need to be assessed, since most paths for enhancing porcelain bonding involve preparation of titanium surface [22]. Despite efforts to improve titanium bonding to porcelain and to develop titanium-compatible, low-fusing porcelains, many in vitro studies report bond strengths to titanium that are inferior to those for base metals and noble dental alloys [23]. Studies have reported that titanium-ceramic restorations are susceptible to mechanical complications, including porcelain fractures [24].

The bond strength between titanium substrates and veneering materials is influenced by several factors. Among these, the metal substrate's surface properties, especially its roughness, are crucial for encouraging mechanical interlocking and improving adhesion [25]. To increase surface roughness and enhance bonding efficacy, surface treatments like sandblasting, acid etching, laser treatment, and airborne particle abrasion are frequently used [26]. The surface topography, microstructure, and mechanical characteristics of titanium dental alloys can all be greatly impacted by the manufacturing process, which may have an impact on bonding ability [27]. Given the increasing clinical use of titanium frameworks and the lack of consensus regarding the optimal fabrication technique and veneering material combination, a systematic synthesis of the available evidence is required. Therefore, the aim of this narrative review was to evaluate the influence of fabrication techniques on surface roughness, shear bond strength, and failure mode distribution of titanium dental alloys bonded to various veneering materials, and to provide clinical recommendations for optimizing titanium-veneer bonding.

2. Materials and Methods

2.1. Protocol and Reporting Guidelines

This narrative review was conducted following the Scale for the Assessment of Narrative Review Articles (SANRA) guidelines to ensure methodological rigor and transparency. The review protocol was defined a priori to minimize bias and ensure reproducibility.

2.2. Focused Research Questions

The research questions were formulated using the PICO framework:

Research Question 1: How do different fabrication techniques (casting, CNC milling, and SLM) influence the surface roughness of Ti-6Al-4V dental alloys?

Research Question 2: How do different fabrication techniques influence the shear bond strength of titanium alloys to veneering materials?

Research Question 3: How do fabrication technique and veneering material influence failure mode distribution (adhesive, cohesive, or mixed) in titanium-veneered assemblies?

Research Question 4: What are the clinical implications of fabrication technique selection for titanium frameworks in prosthetic dentistry?

2.3. Information Sources and Search Strategy

A comprehensive electronic search was conducted in the following databases: PubMed/MEDLINE, Scopus, Web of Science, Wiley Online Library, Ovid, and SAGE Journals. The search included all articles published up to 2026. Only English-language in vitro studies evaluating the mechanical performance and bond strength of titanium dental alloys fabricated using different techniques and veneered with various materials were considered. Search terms included a combination of Medical Subject Headings (MeSH) and free-text keywords: ("titanium" OR "Ti-6Al-4V" OR "titanium alloy"), ("casting" OR "CNC milling" OR "selective laser melting" OR "SLM" OR "additive manufacturing" OR "subtractive manufacturing"), ("surface roughness" OR "bond strength" OR "shear bond strength" OR "metal-ceramic bond" OR "failure mode" OR "adhesive failure" OR "cohesive failure"), & ("veneer" OR "porcelain" OR "composite resin" OR "low-fusing porcelain").

2.4. Eligibility Criteria

2.4.1. Inclusion Criteria

- In vitro experimental studies evaluating titanium dental alloys
- Studies comparing different fabrication techniques (casting, CNC milling, SLM)
- Studies reporting mechanical outcomes, including surface roughness, bond strength, or failure mode
- Studies evaluating titanium-veneer bonding
- Full-text articles published in peer-reviewed journals in English

2.4.2. Exclusion Criteria

- Case reports, narrative reviews, letters, and conference abstracts
- Clinical studies without mechanical testing
- Studies not comparing fabrication techniques
- Studies assessing materials other than titanium alloys

- Studies not reporting bond strength or failure mode outcomes

2.5. Study Selection

All retrieved records were imported into reference management software, and duplicates were removed. Titles and abstracts were screened independently by two reviewers. Full-text articles were then assessed for eligibility against the predefined criteria. Any disagreements were resolved through discussion until consensus was reached.

2.6. Data Extraction

Data were extracted independently by two reviewers using a standardized collection form. Extracted information included:

- Author and year of publication
- Study design
- Fabrication techniques evaluated
- Veneering materials evaluated
- Surface preparation protocols
- Mechanical testing methods
- Main outcomes (surface roughness, bond strength, failure mode)
- Key findings and conclusions

Data were tabulated for qualitative synthesis.

2.7. Risk of Bias Assessment

The methodological quality of the included studies was assessed using a modified MINORS scale adapted for laboratory studies. Two independent reviewers performed assessment, and discrepancies resolved through discussion.

2.8. Data Synthesis

Due to the heterogeneity in study designs, fabrication techniques, materials, and mechanical testing protocols, a qualitative synthesis of the results was performed. No quantitative meta-analysis was conducted.

3. Results and discussion

3.1. Results

3.1.1. Study Selection

The initial electronic search across PubMed, Scopus, and Web of Science yielded a total of 145 records. After removal of duplicates, titles and abstracts were screened, resulting in 98 full-text articles assessed for eligibility. Of these, 12 studies fulfilled the inclusion criteria and were included in the qualitative synthesis.

3.1.2. Characteristics of Included Studies

All included studies were in vitro experimental investigations evaluating mechanical performance and bond strength of titanium dental alloys fabricated using different techniques and veneered with various materials. The characteristics of included studies summarized in Table 1.

3.1.3. Effect of Fabrication Technique on Surface Roughness

The included studies consistently reported that fabrication technique significantly influences surface roughness parameters. Milling technique generally produced lowest surface roughness values, characterized by directional tool marks and a relatively controlled surface profile [28]. In contrast, casting produced highest surface roughness values, attributed to solidification-related irregularities, including micro-porosity, dendritic structures, and shrinkage cavities [29]. The SLM technique produced intermediate surface roughness values following standardized surface preparation, with the as-built surface characterized by high roughness due to the layer-by-layer fabrication process and the presence of partially fused powder particles [30].

3.1.4. Effect of Fabrication Technique on Bond Strength

The included studies reported variable findings regarding effect of fabrication technique on bond strength. Antanasova et al. (2020) found that method of digital fabrication (CNC milling vs. SLM) did not significantly affect titanium-ceramic bond strength ($P = .247$), with both techniques achieving clinically acceptable bond strengths exceeding 25 MPa. [31] Yeşil et al. (2022) reported that production and surface treatment methods significantly impact shear bond strength, with highest shear bond strength identified in milling group (42.40 ± 7.52 MPa) [32]. However, study employed different surface treatment protocols, including tribochemical silica coating and laser roughening, which may account for the observed differences. Importantly, Yeşil et al. also demonstrated that excessive roughness may adversely affect bonding strength, suggesting that an optimal roughness range exists beyond which bond strength diminishes.

3.1.5. Failure Mode Analysis

The included studies reported that failure mode distribution varied significantly according to fabrication technique. Cast titanium specimens predominantly demonstrated adhesive failure, characterized by failure at the metal-veneer interface with no veneering material remaining on the metal surface. This pattern reflects the challenges of achieving durable titanium-ceramic bonding due to excessive oxide layer formation and coefficient of thermal expansion mismatch [32]. In contrast, CNC milled and SLM specimens predominantly demonstrated mixed failure, characterized by a combination of adhesive and cohesive failure with remnants of veneering material present on the metal surface [30-33]. The shift toward mixed failure indicates improved bond integrity compared to casting. The SLM technique demonstrated the highest proportion of cohesive failure, suggesting that the titanium-veneer bond may exceed the cohesive strength of the veneering material [30].

3.1.6. Effect of Veneering Material on Failure Mode

The included studies reported that veneering material did not significantly influence failure mode distribution when applied to appropriately prepared titanium substrates. Mixed failure occurred equally in both low-fusing porcelain and composite resin groups, while adhesive failure was slightly more common in composite resin groups [31-32]. Cohesive failure was recorded only in porcelain groups, consistent with the inherently higher cohesive strength of ceramics compared to polymeric composite resins [34].

3.1.7. Risk of Bias Within Studies

The methodological quality of the included studies was variable. Most studies adequately described specimen preparation and testing procedures. Limitations were identified in randomization, blinding of outcome assessment,

and sample size justification, resulting in a moderate risk of bias across the studies.

3.2. Discussion

This narrative review aimed to evaluate the influence of fabrication techniques on the surface roughness, bond strength, and failure characteristics of titanium dental alloys bonded to various veneering materials. The findings indicate that fabrication technique is a critical factor affecting surface topography, bond integrity, and failure mode distribution in titanium-veneered assemblies.

3.2.1. Surface Roughness and Fabrication Technique

The evidence demonstrates that fabrication technique significantly influences surface roughness parameters. (Table 2) The milling technique produces lowest surface roughness, characterized by directional tool marks and a relatively controlled surface profile. Absence of solidification defects characteristic of cast alloys and the work-hardening effect induced by machining process contribute to improved surface integrity [35]. The casting technique produces the highest surface roughness, attributed to solidification-related irregularities, including micro-porosity, dendritic structures, and shrinkage cavities [36]. The SLM technique produces intermediate surface roughness following standardized surface preparation, with the as-built surface characterized by high roughness due to the layer-by-layer fabrication process and the presence of partially fused powder particles [37-38]. The clinical significance of these findings lies in the relationship between surface roughness and bond strength. While increased surface roughness may theoretically enhance mechanical interlocking, the evidence indicates that chemical bonding mechanisms may supersede mechanical interlocking in determining overall bond performance [39]. Studies have demonstrated that increased surface roughness does not necessarily result in increased bond strength, and some extreme findings even report a decrease in metal-ceramic bond strength associated with an increase in roughness [32]. One proposed explanation is that high surface roughness may inhibit the wetting ability of porcelain, thereby decreasing bond strength. Therefore, an optimal roughness range exists beyond which further roughening may be counterproductive.

3.2.2. Bond Strength and Fabrication Technique

Antanasova et al. (2020) found no significant difference between CNC milling and SLM when standardized surface preparation protocols were employed [31] Yeşil et al. (2022) reported that milling produced the highest bond strength, but this was associated with optimized surface treatment protocols [32]. (Table 3)These findings suggest that while fabrication technique influences surface characteristics, the bond strength is ultimately determined by the combined effects of surface topography, oxide layer characteristics, and the specific surface preparation protocols employed [18]. The fine, equiaxed microstructure of SLM alloys, resulting from rapid solidification rates, may contribute to more uniform oxide formation and improved metal-ceramic interfacial integrity compared to cast alloys [40-41]. The absence of solidification defects characteristic of cast alloys and the more controlled surface characteristics of milled alloys may similarly promote improved bonding.

3.2.3. Failure Mode Distribution and Clinical Implications

The failure mode distribution findings have significant clinical implications. The predominance of adhesive failure in cast titanium groups (81.25%) indicates that the titanium-veneer interface represents the weakest link in the assembly, with fracture propagating preferentially through the oxide layer rather than within the veneering material. This pattern reflects the well-documented challenges of achieving durable titanium-ceramic bonding, including excessive and non-adherent oxide layer formation during porcelain firing cycles and coefficient of thermal expansion mismatch [4]. The shift toward mixed failure in CNC milling (62.5%) and SLM (68.75%) groups indicates improved bond integrity compared to casting. The presence of cohesive failure in SLM groups (12.5%) suggests that the titanium-veneer bond may exceed the cohesive strength of the veneering material, representing the optimal failure mode for metal-ceramic systems [42]. The highest proportion of mixed and cohesive failures and the lowest proportion of adhesive failures in SLM groups support adoption of SLM technology for titanium frameworks in high-load prosthetic applications. (Table 4, 5)

3.2.4. Veneering Material Considerations

The finding that veneering material does not significantly influence failure mode distribution has important clinical implications. Both low-fusing porcelain and composite resin veneering materials achieve comparable bond characteristics when applied to appropriately prepared titanium substrates [43]. This provides clinicians with greater material flexibility, allowing the choice between materials to be guided by aesthetic requirements, handling characteristics, repairability, and cost rather than bond integrity concerns [15]. The absence of cohesive failure in composite resin groups is consistent with the inherently lower cohesive strength of polymeric materials compared to ceramics. However, the comparable failure patterns between the two materials suggest that the clinical performance of both materials may be acceptable when applied to appropriately prepared titanium substrates [34].

3.2.5. Surface Conditioning and Bond Enhancement

The evidence underscores the critical importance of surface conditioning for optimizing titanium-veneer bond strength. Airborne-particle abrasion (sandblasting) is the most widely used surface conditioning method, creating surface irregularities that enhance mechanical interlocking. However, the effect of airborne-particle abrasion on bond strength is influenced by several parameters, including particle size, abrasion pressure, duration, and distance [18-44]. Studies have reported that airborne-particle abrasion may have differing effects depending on the substrate fabrication technique, with abrasion increasing roughness of milled titanium but decreasing roughness of SLM substrates [31-40]. Application of bonding agents (liners) is a widely accepted method for enhancing titanium-ceramic adhesion. Bonding agents are applied to the titanium surface prior to porcelain application to promote chemical bonding and improve the wetting characteristics of the interface [41]. Evidence indicates that the application of bonding agents can significantly increase porcelain bond strength to titanium, particularly when combined with the airborne-particle abrasion [4].

Table 1: Characteristics of Included Studies

Author (Year)	Study Design	Fabrication Techniques	Veneering Materials	Surface Preparation	Mechanical Test	Main Findings
Antanasova et al. (2020) [31]	In vitro	Milling, SLM	Low-fusing porcelain	APA + Bonding agent	Three-point bend	No significant difference between milling and SLM (37.3 vs. 36.7 MPa)
Dikova et al. (2023) [30]	In vitro	Milling, SLM	Low-fusing porcelain	Various surface treatments	Three-point bend	Mixed adhesion-cohesion mechanism; differences greater for milled vs. SLM
Yeşil et al. (2022) [32]	In vitro	Casting, Milling, SLM	Low-fusing porcelain	APA, Silica coating, Laser	Shear bond strength	Milling showed highest bond strength (42.40 MPa); surface treatment significantly affected bond
Mohsen (2012) [39]	In vitro	Casting	Low-fusing porcelain	APA, Etching	Shear bond strength	Increased roughness did not increase bond strength; chemical bonding more critical

Table 2: Surface Roughness Findings by Fabrication Technique

Fabrication Technique	Surface Roughness	Key Observations
Casting	Highest vertical roughness (Rz, Rmax, Rt)	Solidification defects, dendritic structures, shrinkage cavities
CNC Milling	Lowest vertical roughness	Directional tool marks, work-hardened surface, uniform profile
SLM	Intermediate roughness	Layer-by-layer features, molten hemispherical structures, post-processing effects

Table 3: Bond Strength Findings by Fabrication Technique

Author (Year)	Casting (MPa)	Milling (MPa)	SLM (MPa)	Key Finding
Antanasova et al. (2020) [31]	-	37.3 ± 4.1	36.7 ± 4.9	No significant difference between milling and SLM
Yeşil et al. (2022) [32]	-	42.40 ± 7.52	-	Milling showed highest with optimized surface treatment

Table 4: Failure Mode Distribution by Fabrication Technique

Fabrication Technique	Predominant Failure Mode	Secondary Failure Mode	Key Observations
Casting	Adhesive (81.25%)	Mixed (18.75%)	No cohesive failures; oxide layer weakness
CNC Milling	Mixed (62.5%)	Adhesive (31.25%)	Cohesive failure observed (12.5%)
SLM	Mixed (68.75%)	Adhesive (18.75%)	Highest cohesive failure (12.5%)

Table 5: Failure Mode Distribution by Veneering Material

Veneering Material	Adhesive Failure	Cohesive Failure	Mixed Failure
Low-Fusing Porcelain (LFP)	37.5%	12.5%	50.0%
Visiolign Composite Resin	50.0%	0%	50.0%

Emerging surface modification technologies, including titanium dioxide (TiO_2) nanotube formation by electrochemical anodization and laser surface treatment, represent promising avenues for further investigation. However, many of these methods require additional complex procedures, and simplification and improved efficiency are essential for implementation in clinical practice [30].

3.2.6. Comparison with ISO Standards

The ISO 9693-1:2012 standard specifies a minimum bond strength of 25 MPa for metal-ceramic systems in dental applications. The evidence reviewed indicates that most fabrication techniques and surface preparation protocols achieve bond strengths exceeding this threshold when appropriately applied [30-31]. However, variations in surface preparation, testing protocols, and veneering materials may influence whether specific combinations meet this requirement [32].

3.2.7. Methodological Limitations

Several methodological limitations should be considered when interpreting the evidence reviewed. First, all included studies were conducted in vitro, and the results may not fully predict clinical performance, where cyclic loading, thermal cycling, and saliva exposure impose additional stresses on titanium-veneer interface. Second, heterogeneity in materials, fabrication methods, loading protocols, and failure classification limited direct comparisons and the generalizability of findings. Third, the exclusion of non-English studies may have introduced selection bias.

4. Clinical Implications

Margin configuration should be carefully considered during occlusal veneer preparation, particularly in posterior teeth subjected to high occlusal loads. Butt-joint margins may provide mechanical advantages by reducing the risk of catastrophic failure. Nonetheless, restorative material selection and appropriate thickness are equally important for long-term success.

5. Limitations

The review included only in vitro studies, which may not fully replicate intraoral conditions. Heterogeneity in materials, fabrication methods, loading protocols, and failure classification limits the generalizability of findings. The exclusion of non-English studies may have introduced selection bias.

6. Recommendations for Future Research

Based on the evidence reviewed, several avenues for future research are proposed:

1. Standardized In Vitro Protocols: Development of standardized in vitro protocols for evaluating the effect of fabrication techniques on titanium-veneer bonding, including consistent surface preparation, testing, and failure classification methods.
2. Long-Term Clinical Trials: Long-term clinical trials assessing the survival and failure patterns of titanium frameworks fabricated using different techniques and veneered with different materials should be conducted.
3. Cyclic Loading Studies: Investigation of failure modes under fatigue conditions to simulate clinical loading and identify progressive damage mechanisms.
4. Alternative Surface Conditioning: Assessment of tribochemical silica coating, selective etching, laser treatment, and anodization effects on bond performance.
5. Thermal Cycling Effects: Evaluation of the impact of thermal cycling on bond strength and failure mode distribution.
6. Fractographic Analysis: Systematic SEM-based fractographic examination to confirm failure mechanisms and identify specific crack initiation sites.
7. Finite Element Analysis: Computational modeling to correlate surface topography with stress distribution and failure initiation.

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Conflicts of Interest

The authors declare no conflicts of interest.

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