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CAD/CAM CERAMICS IN MODERN PROSTHODONTICS: EVALUATION OF SURFACE TOPOGRAPHY, ROUGHNESS, AND CLINICAL IMPLICATIONS

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Abstract

Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies have revolutionized prosthodontics by enabling the fabrication of restorations with enhanced accuracy, reproducibility, and efficiency. Ceramic materials remain at the forefront of digital restorative dentistry due to their combination of esthetics, mechanical strength, and biocompatibility. Among them, feldspathic ceramics, lithium disilicate, and zirconia represent the most clinically relevant categories, each characterized by distinct microstructural and surface properties. Surface topography and roughness are critical parameters that directly influence adhesion, optical behavior, bacterial colonization, and resistance to wear, thereby shaping both short- and long-term clinical outcomes. Evidence demonstrates that smoother ceramic surfaces improve plaque resistance, gloss retention, and antagonist preservation, while improper finishing can compromise restoration durability. Lithium disilicate offers an optimal balance of translucency and strength, feldspathic ceramics excel in esthetics but require reinforcement, whereas zirconia provides superior fracture toughness with esthetic limitations. Recent innovations, including zirconia-reinforced lithium silicate and nanoparticle-based coatings, illustrate ongoing efforts to optimize surface behavior. Clinical performance is therefore determined not only by material choice but also by processing parameters and finishing protocols. Looking ahead, nanotechnologies and bioactive coatings promise to further enhance the biological and mechanical integration of CAD/CAM ceramics, consolidating their role as essential materials in modern prosthodontics.

Keywords: CAD/CAM ceramics, surface roughness, topography, lithium disilicate, zirconia, feldspathic ceramics.

Introduction

The continuous evolution of biomaterials and digital technologies has profoundly influenced modern prosthodontics, where ceramics occupy a central role due to their balance of esthetics, functionality, and biocompatibility. Research on bone substitutes and biomaterials demonstrates how material science advances can directly impact clinical outcomes, highlighting the same trend seen in dentistry, where restorative solutions increasingly rely on high-performance materials tailored to patient needs [1]. The introduction of computer-aided design and computer-aided manufacturing (CAD/CAM) has revolutionized dental workflows, improving accuracy, efficiency, and reproducibility while reducing human error [2]. These technologies have redefined restorative dentistry by offering clinicians the ability to fabricate restorations with improved marginal fit, durability, and esthetic integration.

At the same time, the growing clinical demand for reliable and longlasting restorative solutions parallels innovations in other fields such as alveolar bone regeneration and orthopedic surgery, where biomaterials and digital technologies converge to optimize functional recovery [3,4]. Within dentistry, the digitization of workflows has become a global trend, shifting conventional practices toward computer-based protocols that enable both precision and personalization of treatments [5]. The adoption of CAD/CAM systems has expanded rapidly, supported by evidence showing their effectiveness in reducing chairside time, minimizing material waste, and enabling the use of advanced ceramics with predictable outcomes [6].

Among the restorative materials processed through CAD/CAM, ceramics stand out for their superior optical and mechanical properties. Monolithic CAD/CAM ceramics have been extensively studied for their optical performance, translucency, and thickness-dependent behavior, which are crucial for esthetic success [7]. Their surface characteristics topography, roughness, and gloss directly influence not only visual integration but also biological interactions within the oral cavity. For example, smooth surfaces limit bacterial adhesion and facilitate oral hygiene, while rough surfaces may compromise periodontal health. Customization of materials and workflows has further demonstrated clinical utility in complex cases, such as patients with systemic diseases requiring specialized restorative approaches [8].

Long-term clinical studies confirm that CAD/CAM-processed ceramics, particularly lithium disilicate, can provide survival rates comparable to or exceeding those of traditional metal-ceramic restorations. Their performance is strongly associated with surface quality, which impacts adhesion, resistance to fracture, and esthetic longevity [9]. As such, clinicians must evaluate not only the intrinsic properties of ceramic materials but also the effect of processing techniques and finishing protocols on their surface behavior.

Overall, the development of ceramic CAD/CAM materials has provided clinicians with a versatile range of restorative options, each characterized by unique advantages and limitations [10]. The understanding of surface properties, combined with knowledge of CAD/CAM technology, is therefore fundamental in ensuring predictable outcomes. This review aims to provide a comparative perspective on the surface properties of feldspathic ceramics, lithium disilicate, and zirconia, emphasizing their clinical significance in prosthodontics.

Overview of CAD/CAM ceramics

Ceramic CAD/CAM materials have become an essential component of restorative dentistry, combining precision of digital fabrication with the clinical benefits of ceramics [10]. These materials are used across a wide spectrum of prosthetic applications, offering clinicians a choice based on esthetic demands, mechanical requirements, and biological considerations. Among them, feldspathic ceramics, lithium disilicate, and zirconia remain the most widely investigated, while hybrid and resin-ceramic materials are continuously being developed to bridge mechanical strength and esthetic integration.

Feldspathic ceramics are appreciated for their translucency and ability to mimic natural enamel, although their limited fracture resistance restricts their use primarily to anterior restorations or veneering applications [11]. Zirconia, in contrast, is recognized for its exceptional toughness and resistance to mechanical stress, making it suitable for high-load areas, though its relative opacity may compromise esthetics [12]. Recent advances in resin composites reinforced with zirconia nanoparticles illustrate ongoing efforts to improve surface quality, strength, and durability of new restorative materials [13].

Table 1. Overview of CAD/CAM ceramics

Ceramic type	Main characteristics	Clinical applications	Supporting references
Feldspathic ceramics	Excellent translucency, high esthetics, but limited fracture resistance.	Anterior veneers, low-stress restorations.	[11,21]
Lithium disilicate	Balance between esthetics and mechanical strength; good bonding capacity.	Crowns, veneers, inlays, onlays in anterior and posterior areas.	[15,22,23]
Zirconia	Superior toughness, high strength, low translucency; resistant to wear.	Posterior crowns, bridges, implant-supported restorations.	[12,17,21-24]
Resin-ceramics / hybrids	Flexibility, easier milling, enhanced shock absorption; variable optical stability.	Minimally invasive restorations, temporary or permanent crowns.	[13,14,18–20]

Table 1 summarizes the main CAD/CAM ceramic categories, describing their fundamental characteristics, clinical applications, and relevant literature. Feldspathic ceramics excel in esthetics but lack strength, lithium disilicate balances translucency and durability, zirconia provides unmatched toughness, while resin-ceramics and hybrids offer versatile performance. Together, these materials illustrate the diversity of CAD/CAM ceramics and emphasize the importance of selecting the appropriate restorative option based on clinical demands.

Surface properties, including roughness and color stability, are decisive for clinical outcomes. Systematic reviews confirm that different surface treatments significantly affect the performance of resin-ceramics, impacting their long-term esthetic behavior [14]. Glass-ceramics, particularly lithium disilicate, remain a cornerstone of prosthetic dentistry, offering a balance between optical integration and reliable strength [15]. Microscopic analyses, such as scanning electron microscopy and atomic force microscopy, provide valuable insights into how ceramic microstructure determines surface topography and clinical performance [16].

Parallels can be drawn from orthopedics and biomaterials research, where comparative evaluations of implant and prosthetic surfaces highlight the role of microstructure and finishing in durability [17,18]. Similarly, studies in implant dentistry have emphasized how surface modifications directly affect biological integration and marginal bone stability [19]. Advanced coatings and treatments, such as selenium nanoparticle layers, also illustrate the importance of surface engineering in improving biocompatibility and clinical longevity [20].

Surface properties and their clinical significance

The surface properties of CAD/CAM ceramics play a pivotal role in determining their clinical success, influencing esthetic performance, biological compatibility, and mechanical durability. Feldspathic ceramics, for example, have been subjected to chemical tempering techniques aimed at strengthening their surface integrity and improving resistance to mechanical stress, a factor essential for long-term stability under functional load [21]. Lithium disilicate has emerged as a versatile restorative material, offering a combination of translucency and mechanical strength that allows its application in both anterior and posterior regions [22,23]. Recent innovations, such as zirconia-reinforced lithium silicate ceramics, further integrate toughness with esthetic qualities, reflecting the trend toward multiphase materials designed for optimal surface behavior [24].

Table 2. Surface properties and their clinical significance

Property / Aspect	Clinical significance	Supporting references
Roughness (Ra, Rz values)	Influences plaque accumulation, antagonist wear, and gloss retention; smoother surfaces improve esthetics and hygiene.	[21,26,27,29]
Topography & microstructure	Determines crack propagation, fatigue resistance, and bonding capacity with resin cements.	[16,22,28]
Optical properties (translucency, gloss, color stability)	Critical for esthetic integration and long-term appearance of restorations; strongly affected by surface finishing.	[15,23,24,30]
Mechanical strength	Improved by tempering or reinforcement; essential for load-bearing restorations.	[21,23,24]
Surface treatments (glazing, polishing, etching)	Optimize adhesion, reduce roughness, and increase resistance to staining; outcomes depend on the chosen protocol.	[25,26,30]
Bacterial adhesion	Rougher surfaces favor microbial colonization; smoother finishes reduce periodontal risk.	[27,29]
Wear resistance	Protects against antagonist abrasion and maintains restoration morphology.	[23,24,28]

Table 2 outlines the main surface properties of CAD/CAM ceramics and their clinical implications. Roughness, topography, optical qualities, and bacterial adhesion determine restoration longevity, esthetics, and biological safety. Mechanical strength and wear resistance depend on both microstructure and finishing protocols, while surface treatments play a decisive role in optimizing clinical performance, supporting evidence-based material selection.

Clinical evidence supports the long-term performance of CAD/CAM ceramics, with retrospective studies on CEREC restorations demonstrating high survival rates when appropriate surface conditioning and adhesive protocols are applied [25]. Comparative studies of implant and restorative surfaces highlight that mechanical and optical properties are strongly influenced by surface treatments, underlining the need for customized finishing strategies [26]. Surface roughness is particularly critical, as it affects gloss retention, plaque accumulation, and antagonist wear, while systematic reviews confirm that outcomes are highly dependent on both material composition and polishing system employed [27].

From a mechanical perspective, the way lithium disilicate and metasilicate ceramics respond to microgrinding and polishing influences crack initiation and fatigue resistance, directly impacting their service life [28]. The biological implications are equally significant, as smoother ceramic surfaces are less prone to bacterial adhesion, thereby lowering the risk of secondary complications [29]. Moreover, optical characteristics such as color stability, translucency, and wettability are closely tied to finishing and surface treatments, making these properties decisive for esthetic success [30].

Comparative evaluation of CAD/CAM ceramics: surface topography, roughness, and influencing factors in clinical performance

The evaluation of CAD/CAM ceramic restorations requires a comprehensive understanding of how surface characteristics such as topography and roughness influence clinical performance. Glass-ceramics, especially lithium disilicate, have been widely studied for their optical and mechanical behavior, providing a reliable basis for prosthodontic applications [15]. These materials balance translucency with mechanical resistance, offering a functional and esthetic solution in both anterior and posterior restorations. Their microstructural organization allows controlled finishing and polishing, which significantly impacts long-term esthetic and mechanical outcomes.

Advances in microscopy and surface characterization methods, including scanning electron microscopy and atomic force microscopy, have made it possible to evaluate ceramic topography with great precision [16]. These methods highlight how different materials display unique surface morphologies, which directly influence bonding strength, wear resistance, and biological interactions. Zirconia, for instance, demonstrates superior mechanical toughness but presents challenges regarding translucency. Surface treatments such as glazing and polishing are essential to optimize its clinical performance, especially when esthetic requirements are high [17]. Reinforced composites and hybrid ceramics enriched with zirconia nanoparticles represent ongoing innovations, aiming to combine enhanced strength with improved surface smoothness and stability [18].

The importance of surface optimization is supported not only in dental prosthetics but also in orthopedics, where similar principles apply to implant surfaces and prosthetic components. Studies on marginal bone loss and surface design in dental implants confirm that microstructural characteristics and finishing methods critically affect biological integration [19]. Furthermore, nanoparticle coatings, such as selenium on titanium mesh, exemplify strategies designed to improve surface biocompatibility, offering insights that can be transferred to dental ceramics [20]. Feldspathic ceramics, though less resistant than lithium disilicate or zirconia, have been strengthened through chemical tempering, increasing their ability to withstand functional stresses [21].

Lithium disilicate remains a reference material for CAD/CAM prosthodontics due to its optical qualities and reliable strength. Its ability to mimic natural dentition makes it particularly useful in anterior zones, while zirconia-reinforced lithium silicate materials integrate toughness and esthetic performance in a single restorative option [22–24]. Retrospective studies demonstrate the high survival rates of CAD/CAM lithium disilicate restorations over five years, provided that appropriate adhesive and finishing protocols are implemented [25]. These findings emphasize that clinical longevity depends not only on the intrinsic qualities of the material but also on how surface treatments are applied.

Comparative analyses of dental implants confirm that roughness, gloss, and topography vary significantly between materials and processing methods, influencing both mechanical and biological outcomes [26]. Surface roughness remains a critical factor: higher values promote bacterial adhesion and antagonist wear, while smoother surfaces preserve gloss and facilitate plaque control [27]. Grinding and polishing protocols applied to lithium disilicate and lithium metasilicate ceramics alter surface integrity and resistance to crack propagation, highlighting the importance of proper finishing in extending restoration lifespan [28]. From a biological standpoint, smooth ceramic surfaces discourage bacterial colonization, improving periodontal outcomes and long-term oral health [29].

Equally important are the optical properties affected by surface treatments. Color stability, translucency, and wettability are essential for esthetic integration and are strongly influenced by glazing, polishing, or etching techniques [30]. Without appropriate finishing, even advanced ceramics may lose translucency, develop surface stains, or compromise patient satisfaction. This underscores the interdependence between surface properties and clinical outcomes: mechanical resilience, esthetics, and biological safety are all governed by how well the surface of CAD/CAM ceramics is optimized.

Conclusions

The comparative evaluation of CAD/CAM ceramics clearly demonstrates that surface properties such as topography, roughness, gloss, and color stability are decisive for the clinical success and longevity of dental restorations. Feldspathic ceramics, lithium disilicate, and zirconia each provide unique advantages, yet their performance is largely dependent on how surface treatments and finishing protocols are applied. Clinical evidence highlights that smoother surfaces not only improve esthetic outcomes by maintaining translucency and gloss but also enhance biological compatibility by reducing bacterial adhesion and plaque accumulation. At the same time, mechanical properties such as fracture resistance and fatigue behavior are strongly influenced by microstructural characteristics and by the precision of CAD/CAM processing parameters. Looking forward, innovations in nanotechnology, surface coatings, and hybrid materials will continue to optimize the balance between esthetics, durability, and biological performance, confirming CAD/CAM ceramics as a cornerstone of modern prosthodontics.

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