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COMPARATIVE INSIGHTS INTO SURFACE PROPERTIES OF CAD/CAM-PROCESSED CERAMIC MATERIALS: A REVIEW

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ABSTRACT

The development of CAD/CAM technology has significantly transformed restorative dentistry, providing clinicians with improved accuracy, reproducibility, and efficiency in the fabrication of ceramic restorations. Among the most widely used CAD/CAM ceramics are feldspathic ceramics, lithium disilicate, and zirconia, each with distinct microstructural and surface characteristics that influence their clinical performance. Surface properties such as roughness, topography, gloss, translucency, and color stability play a decisive role in determining the esthetic integration, mechanical durability, and biological behavior of these materials. Smooth, well-finished surfaces reduce bacterial adhesion, plaque accumulation, and antagonist wear, while also preserving optical qualities over time. Conversely, improper finishing protocols may compromise both function and longevity. Comparative analyses reveal that lithium disilicate provides an optimal balance between esthetics and strength, feldspathic ceramics offer excellent translucency with moderate resistance, while zirconia remains unmatched in terms of fracture toughness, albeit with esthetic limitations. The performance of these materials is also highly dependent on processing parameters, surface treatments, and finishing techniques. Future research directions aim to integrate nanotechnologies and advanced coatings to optimize surface properties, offering enhanced long-term stability and clinical predictability. CAD/CAM ceramics thus represent a cornerstone of modern prosthodontics, bridging innovation in material science with clinical excellence.

Keywords: CAD/CAM ceramics, surface properties, feldspathic ceramics, lithium disilicate, zirconia, restorative dentistry, surface treatments.

Introduction

The continuous development of biomaterials research and clinical dentistry has led to significant advances in restorative solutions, where ceramics remain one of the most widely investigated categories of materials due to their unique combination of mechanical strength, aesthetics, and biocompatibility [1].

In this context, digital dentistry and computer-aided design/computer-aided manufacturing (CAD/CAM) technologies have transformed the way ceramic restorations are fabricated, offering superior accuracy, reproducibility, and efficiency compared to conventional methods [2]. The demand for restorations that are both functional and esthetically pleasing has emphasized the importance of studying the surface properties of dental ceramics, since they directly influence clinical outcomes such as mechanical stability, adhesion to resin cements, resistance to wear, and biological integration.

The need for advanced materials is also highlighted in other medical fields, such as orthopedic or reconstructive surgery, where innovations in biomaterials have been correlated with improved clinical performance [3,4]. These parallels strengthen the idea that in dentistry, too, continuous innovation in material science and processing technologies is required to meet clinical expectations.

The adoption of CAD/CAM in prosthodontics represents not only a technological improvement but also a paradigm shift, redefining workflows from diagnosis to final restoration [5,6]. For ceramics in particular, the use of digital workflows has facilitated the processing of a wide range of restorative materials, including feldspathic ceramics, lithium disilicate, and zirconia, each presenting distinct surface characteristics that must be thoroughly evaluated.

Among the most clinically relevant aspects of surface evaluation are topography and optical behavior, which determine the esthetic integration of the restoration within the oral cavity [7]. Surface roughness has a critical role not only in terms of polishability and gloss retention but also in the biological response, as it can influence plaque accumulation and periodontal health. Moreover, in special clinical contexts such as patients with systemic conditions, custom ceramic or ceramic-based restorations processed via CAD/CAM can play an important role in improving oral function and overall quality of life [8].

Long-term studies comparing the clinical performance of different types of crowns have revealed that lithium disilicate glass-ceramic restorations produced through CAD/CAM can offer survival rates comparable to or superior to traditional metal-ceramic alternatives, with surface stability being a determining factor in their success [9]. Consequently, clinicians must not only focus on the intrinsic properties of these materials but also on the ways surface treatments, finishing, and polishing can influence their clinical effectiveness.

Current evidence also emphasizes that ceramic materials processed via CAD/CAM exhibit considerable variability in terms of microstructural composition and surface properties, which must be carefully considered when selecting the appropriate restorative material for each clinical case [10]. Understanding these differences is essential for optimizing adhesion protocols, improving wear resistance, and ensuring esthetic predictability. Thus, the evaluation of surface properties in feldspathic, lithium disilicate, and zirconia ceramics becomes crucial in providing reliable, durable, and patient-centered restorative solutions.

Overview of CAD/CAM ceramics

Ceramic materials processed via CAD/CAM systems have become central in restorative dentistry due to their ability to combine strength, biocompatibility, and excellent esthetics. Their successful integration into clinical workflows requires an understanding of their classification, microstructural differences, and surface behavior [10]. Glass-ceramics, particularly lithium disilicate, are among the most widely used materials because they balance esthetic translucency with mechanical resistance, making them suitable for both anterior and posterior restorations [11]. Zirconia, on the other hand, has gained attention due to its outstanding fracture toughness and durability, although its opacity remains a limitation in highly esthetic areas [12]. Recent innovations also include reinforced composites and hybrid ceramics, which attempt to bridge the gap between strength and esthetic performance [13].

The surface properties of CAD/CAM ceramics are crucial for their clinical longevity. Parameters such as surface roughness, gloss, and color stability are directly influenced by both material composition and the finishing protocol applied after milling [14]. Glass-ceramics, for instance, present excellent esthetic integration but require precise surface treatment to ensure reliable adhesion and durability [15]. Advanced microscopy techniques, including SEM and AFM, have allowed detailed characterization of ceramic surfaces, offering valuable insight into how microstructure affects performance [16].

Beyond dental applications, the principles of surface optimization are also studied in orthopedics, where comparative analyses of titanium and composite materials provide transferable knowledge to the field of prosthodontics [17,18]. Furthermore, research into peri-implant tissues highlights how surface modifications can impact marginal bone stability and long-term success, reinforcing the importance of surface design in all biomaterial applications [19,20].

Surface properties and their clinical significance

The clinical success of CAD/CAM ceramics is closely related to their surface properties, as these characteristics directly affect esthetics, adhesion, mechanical strength, and biological response. Feldspathic ceramics, for instance, have been subjected to chemical tempering techniques to enhance their surface integrity and increase their resistance to mechanical stresses, with significant improvements in longevity being reported [21].

Lithium disilicate, on the other hand, is valued for its balance of translucency and mechanical durability, providing restorations that meet both functional and esthetic demands [22,23]. Moreover, recent developments such as zirconia-reinforced lithium silicate ceramics aim to integrate the best properties of both materials, combining enhanced toughness with superior surface smoothness [24].

Surface finishing and treatments also play a critical role in determining clinical outcomes. Studies show that CAD/CAM ceramic restorations can maintain high survival rates over time, provided that surface conditioning protocols such as polishing, glazing, or etching are correctly applied [25].

Comparative analyses of surface properties across different implant and restorative materials highlight that roughness, gloss, and topography are not only material-dependent but also strongly influenced by the finishing method [26]. Surface roughness, in particular, affects both wear of opposing dentition and the accumulation of plaque, which can compromise periodontal health [27].

Microstructural composition and processing methods also determine how ceramics respond to mechanical and tribological stresses. For example, lithium disilicate and lithium metasilicate ceramics exhibit different behaviors under grinding and polishing, which directly impacts surface integrity [28]. Furthermore, the degree of surface roughness is correlated with bacterial adhesion, suggesting that smoother ceramics are more favorable for long-term oral health [29]. Esthetic properties such as color stability, translucency, and wettability are also strongly affected by surface treatments, influencing both the visual integration of the restoration and its resistance to staining in the oral environment [30].

Table 1. Surface properties and their clinical significance

Property / aspect	Clinical significance	Supporting references
Roughness (Ra, Rz values)	Influences plaque accumulation, antagonist wear, 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; affected by surface finishing and treatments.	[15,23,24,30]
Mechanical strength	Enhanced by chemical 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; protocol-dependent outcomes.	[25,26,30]
Bacterial adhesion	Rougher surfaces favor microbial colonization; smooth finishes reduce risk of periodontal complications.	[27,29]
Wear resistance	Prevents excessive abrasion of opposing dentition and maintains restoration morphology.	[23,24,28]

Table 1 summarizes the main surface properties of CAD/CAM ceramics, highlighting their clinical significance and providing supported references. Properties such as roughness, optical behavior, and bacterial adhesion are key determinants of restoration longevity, esthetics, and biological performance, emphasizing the importance of surface optimization in modern prosthodontics.

Comparative evaluation of CAD/CAM ceramics: surface factors, clinical implications, and influencing variables

Ceramic materials used in restorative dentistry have evolved considerably over the last decades, with CAD/CAM processing enabling high-precision fabrication and consistency in clinical outcomes. Among these, feldspathic ceramics, lithium disilicate, and zirconia-based ceramics represent the three principal categories of interest, each with unique surface characteristics that influence performance and clinical longevity. Glass-ceramics, including lithium disilicate, are highly valued for their optical integration and balance between strength and translucency, making them one of the most frequently indicated restorative materials in prosthodontics [15]. The composition and microstructural arrangement of glass-ceramics also allow tailored surface finishing, which is essential for their esthetic and functional durability.

Recent advancements in imaging techniques have enabled detailed surface characterization of CAD/CAM ceramics.

Microscopic approaches, such as scanning electron microscopy and atomic force microscopy, provide crucial insight into surface roughness and morphology, confirming that each ceramic category presents distinct microstructural patterns influencing both mechanical and biological performance [16]. For instance, zirconia demonstrates remarkable mechanical strength and wear resistance, but its relatively low translucency may limit its use in anterior esthetic restorations [17]. In parallel, innovations in composite and hybrid ceramics have attempted to overcome these limitations by incorporating reinforcements such as zirconia nanoparticles, with the aim of improving surface smoothness and mechanical stability [18].

The clinical implications of surface properties are particularly evident in implantology and restorative dentistry. It is well established that the degree of roughness significantly influences bacterial adhesion and plaque accumulation, which can compromise the long-term prognosis of both fixed and implant-supported restorations [19]. Surface modifications, whether through glazing, polishing, or nano-coatings, are critical for optimizing performance and reducing biological complications [20]. Moreover, feldspathic ceramics have been subjected to chemical tempering protocols designed to enhance their resistance to mechanical fatigue, an important aspect for ensuring durability under functional load [21].

Lithium disilicate remains a material of reference in CAD/CAM prosthodontics, combining a favorable esthetic profile with satisfactory mechanical resilience. Its ability to mimic natural dentition has made it a popular choice for anterior restorations, while zirconia-reinforced lithium silicate ceramics provide an intermediate solution that integrates esthetics with improved toughness [22–24]. Retrospective studies confirm the clinical reliability of lithium disilicate restorations over periods exceeding five years, provided that appropriate surface conditioning and adhesive protocols are implemented [25]. At the same time, comparative analyses of implant surfaces demonstrate that not only the ceramic composition but also the surface finishing and treatment strongly determine clinical outcomes [26].

Surface roughness is a central determinant of restoration success. Evidence suggests that gloss retention and plaque resistance are directly linked to the finishing protocols employed. Polishing and glazing can reduce roughness, minimize antagonist wear, and enhance long-term esthetic performance. However, differences between polishing systems and restorative materials can yield variable results, making it essential to adapt surface treatments to each ceramic type [27]. Furthermore, microstructural properties of lithium disilicate and metasilicate ceramics influence how they respond to tribological stresses during grinding and polishing, with implications for crack formation and material fatigue [28].

The biological dimension of surface optimization cannot be overlooked. Studies confirm that ceramics with smoother surfaces exhibit reduced bacterial adhesion compared to rougher counterparts, underscoring the importance of surface integrity for oral health [29]. Color stability and translucency are also closely related to surface treatments, as inappropriate finishing can alter optical characteristics and compromise esthetic integration [30].

Lithium disilicate, for example, demonstrates excellent esthetic outcomes, but only when its surface is meticulously polished or glazed to resist staining and maintain translucency.

Conclusions

The comparative evaluation of feldspathic ceramics, lithium disilicate, and zirconia processed through CAD/CAM technology highlights that surface properties are a decisive factor for clinical success and long-term survival of dental restorations. These characteristics determine not only the mechanical strength and functional stability of the materials but also the predictability of restorative outcomes.

Surface-related aspects such as roughness, topography, translucency, and color stability extend beyond the esthetic integration of restorations and have a direct influence on biological behavior, including plaque accumulation and antagonist wear. By carefully controlling these parameters, clinicians can ensure both esthetic satisfaction and oral health preservation.

The overall performance of CAD/CAM ceramics is strongly conditioned by technological parameters, including milling protocols, finishing procedures such as glazing and polishing, and chemical surface treatments. These variables are essential in determining adhesive performance, fracture resistance, and the maintenance of optical properties over time.

Looking forward, continuous progress in material development and surface optimization techniques will further enhance the functional and esthetic qualities of CAD/CAM restorations. The integration of mechanical durability, natural esthetics, and biocompatibility positions advanced ceramics as a cornerstone in modern prosthodontics, with CAD/CAM workflows driving innovation and clinical excellence.

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