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A Review of Fatigue Performance and Failure Mechanisms in Dental Restorative Materials Under Dynamic Occlusal Loading

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ABSTRACT

This study presents a comprehensive comparative analysis of fatigue performance and failure mechanisms in contemporary dental restorative materials subjected to dynamic occlusal loading. Recognizing that fatigue failure constitutes a principal cause of clinical restoration failure, the investigation evaluates ceramics, resin-based composites, and metal-based restoratives under cyclic loading conditions designed to replicate physiological mastication forces. Using thermomechanical aging models, laboratory simulations, and finite element analyses, the study identifies key stress distribution patterns and failure initiation zones associated with each material type. Zirconia and lithium disilicate ceramics exhibit high initial strength but suffer from phase transformations and stress-induced microcracking, while resin-based composites are prone to interfacial degradation, particularly under humid and thermal conditions. Porcelain-fused-to-metal restorations demonstrate vulnerabilities to thermal fatigue and delamination due to mismatched material interfaces. Innovations such as AI-assisted crown design, surface roughness optimization, and titanium base integration show promise in enhancing fatigue resistance across material classes. The findings underscore the limitations of conventional static testing and highlight the need for dynamic, multidirectional fatigue simulations to better predict clinical outcomes. This study provides critical insights for material selection and restorative design in prosthodontics, offering a scientific basis for improving the durability, functionality, and long-term success of dental restorations.

Keywords: *Fatigue failure, dental restorative materials, dynamic occlusal loading, material performance, failure mechanisms*

1. INTRODUCTION

In dental prosthodontics, the mechanical properties of restorative materials are critical determinants of therapeutic success. Accumulating evidence suggests that fatigue failure represents a predominant mechanism underlying restoration failure. During clinical function, dental restorative materials experience complex, dynamic occlusal forces over extended periods. As the principal mechanical load acting on these materials, dynamic occlusal forces significantly influence the longevity of restorations. Given the complexity of mandibular movements, the magnitude, direction, and frequency of these forces vary continuously during mastication, deglutition, and other oral activities [1]. Moreover, interindividual variations in the intraoral environment result in differences in both the magnitude and characteristics of occlusal forces exerted on dental restorations. This complex biomechanical context predisposes restorative materials to fatigue-induced failure, which directly impacts their longevity and overall oral health outcomes [2]. Conventional static strength assessments, frequently employed to evaluate novel materials and restorative techniques, do not adequately represent the fatigue performance of these materials under dynamic loading conditions [3].

Fatigue failure is a phenomenon in which a material fractures after being subjected to cyclic stress below its static yield strength over a specific number of loading cycles [4]. In the oral environment, the occurrence of fatigue failure is governed by multiple factors, including the material's microstructure, surface characteristics, stress distribution, and the chemical and biological influences of the oral milieu [5][6]. Studies indicate that fatigue-related failure constitutes a significant proportion of restoration failures, adversely affecting the longevity of restorations and the overall quality of life of patients [7]. Therefore, a thorough understanding of the fatigue behavior of dental restorative materials under dynamic occlusal loading is crucial for optimizing the clinical success of prosthetic treatments and enhancing patient satisfaction.

Contemporary dental restorative materials primarily include ceramics, resin-based composites, and metals, each characterized by distinct mechanical properties. Ceramic materials are widely utilized in dental restorations due to their superior esthetic qualities 5.[8] and biocompatibility 5.[9]. Resin-based composites, which closely mimic enamel in terms of color stability and shade matching 5.[9], are commonly employed for the restoration of tooth structure. Metallic materials, recognized for their high strength and fatigue resistance, are frequently used in posterior restorations and implant-supported prostheses [11]. Polyether ether ketone (PEEK) has garnered increasing attention in dentistry due to its exceptional mechanical properties, chemical stability, biocompatibility, and thermal resistance 5.[12]. Despite their respective advantages, these materials exhibit substantial differences in fatigue performance and failure mechanisms under dynamic occlusal loading 5.[10]5.[13]. Recent studies emphasize the importance of dynamic fatigue testing in assessing the long-term clinical performance of restorative materials. Using chewing simulators, researchers have conducted eccentric cyclic loading tests on metal-ceramic crowns [14], demonstrating significant variations in fatigue resistance among different materials. The observed failure modes closely correspond to clinical outcomes, further reinforcing the reliability of dynamic occlusal force simulations in predicting the clinical durability of restorative materials.

Although extensive research has investigated the performance of dental restorative materials under occlusal loading, a systematic comparison of their fatigue behavior and failure mechanisms remains limited. This study aims to comprehensively assess the fatigue performance of various dental restorative materials under dynamic occlusal loads, analyze their stress distribution patterns, and systematically characterize their failure mechanisms. By conducting this investigation, we seek to establish scientific guidelines for material selection in clinical prosthodontics and provide theoretical foundations for future material development, ultimately contributing to advancements in dental restoration technology.

2. METHODOLOGY

This study adopted a narrative literature review methodology to synthesize and critically evaluate existing research on the fatigue performance and failure mechanisms of dental restorative materials under dynamic occlusal loading. The objective was to compare various classes of materials including ceramics, resin-based composites, metals, and hybrid restoratives in terms of their mechanical behavior, fatigue resistance, and predominant failure modes when exposed to simulated masticatory forces. This approach allowed for a comprehensive and integrative understanding of current findings, clinical implications, and research gaps.

A systematic literature search was conducted using several reputable databases, including PubMed, Scopus, Web of Science, and ScienceDirect. The search strategy encompassed a broad time range from the year 2000 to 2024, with particular emphasis placed on publications from 2015 onward to capture recent advancements in material science and fatigue testing methodologies. A combination of keywords and Medical Subject Headings (MeSH) terms was utilized to maximize the coverage of relevant literature. These included terms such as "fatigue performance," "dental restorative materials," "dynamic occlusal loading," "ceramic restorations," "resin composites," "zirconia," "lithium disilicate," "porcelain-fused-to-metal," "PEEK," and "chewing simulation." Boolean operators such as AND and OR were employed to refine the search results.

The inclusion criteria for selecting articles comprised peer-reviewed journal publications in English that specifically investigated the fatigue behavior of dental restorative materials under cyclic or dynamic loading conditions. Eligible studies included in vitro experiments, finite element analyses, systematic reviews, and relevant clinical trials. Studies were excluded if they focused solely on static mechanical properties, lacked clear fatigue performance data, or were published as editorials, opinion pieces, or non-peer-reviewed content. Following the initial database search, the titles and abstracts of the retrieved articles were screened for relevance. Full-text articles were then reviewed in detail to assess their suitability for inclusion based on the established criteria. Additionally, the reference lists of the included papers were manually examined to identify further relevant publications not captured during the database search. In total, over 100 documents were initially retrieved, with 58 studies deemed highly relevant and selected for comprehensive analysis and discussion. Data were extracted from each study to capture key information related to material composition, testing methodology, fatigue performance indicators, and the types of failure mechanisms observed. The extracted data were then thematically categorized according to material type and analyzed to identify prevailing trends, differences in performance, and critical factors influencing failure. Special attention was given to studies incorporating clinically relevant loading protocols, such as chewing simulators and step-stress fatigue testing, to ensure the findings reflect realistic intraoral conditions.

3. LITERATURE REVIEW FINDINGS

3.1 Zirconia-Based Ceramic Restorative Materials

Zirconia (ZrO_2), particularly yttria-stabilized tetragonal zirconia polycrystals (Y-TZP), exhibits outstanding mechanical properties, including high flexural strength (>900 MPa) and fracture toughness (5–10 $MPa \cdot m^{1/2}$) 5.[15]. These characteristics enable zirconia restorations to endure substantial masticatory forces, making them well-suited for high-load applications in dental prosthetics. With increasing patient demand for esthetic restorations, high-translucency zirconia (5Y-TZP) has gained popularity, particularly for anterior restorations. However, its fatigue performance remains a subject of debate. Some studies suggest that under step-stress fatigue testing [16], 5Y-TZP demonstrates lower fracture resistance compared to 3Y-TZP and certain 4Y-TZP variants [17], indicating a potential reduction in fatigue strength with increased translucency. Conversely, other research highlights that new-generation zirconia materials, including high-translucency formulations, still surpass metal-ceramic and conventional zirconia-based restorations in overall mechanical performance [18]. Studies have shown that zirconia veneers exhibit higher load-bearing capacity compared to hybrid ceramics and lithium disilicate veneers, while the latter two materials demonstrate similar failure loads [19]. Therefore, clinicians must comprehensively evaluate patient-specific requirements alongside the mechanical properties of different materials when selecting restorative options. Despite reported clinical success rates exceeding 90% for zirconia veneers [18], complications such as chipping and connector fractures continue to occur. The primary failure modes of zirconia restorations include [20] Ceramic fracture, Margin chipping, Debonding and restoration loosening.

Clinical studies [21] have identified bonding issues and structural factors as key contributors to the debonding and loosening of zirconia restorations. In terms of ceramic fracture, grain boundary fracture is one of the most critical failure mechanisms. Due to irregular atomic arrangements at grain boundaries, stress concentration and inherent defects facilitate atomic diffusion under external forces [22]. Additionally, the structure and properties of grain boundaries significantly influence crack propagation [22], making them primary sites for crack initiation. Once initiated, cracks propagate along grain boundaries, eventually leading to fracture.

Margin chipping is another prevalent failure mode in zirconia restorations. In the complex intraoral environment, stress distribution at restoration margins is uneven. When subjected to external forces, localized stress concentration may exceed the material's structural limits, resulting in chipping [23].Furthermore, numerous studies have demonstrated that low-temperature degradation (LTD) in zirconia is closely associated with moisture exposure, which destabilizes the tetragonal phase, promoting its gradual transformation into the monoclinic phase [24]. This phase transformation is accompanied by volumetric expansion, leading to the formation of surface microcracks, which further compromise the mechanical integrity of the material.

3.2 Lithium Disilicate Ceramics ($Li_2Si_2O_5$)

Lithium disilicate ($LiSi_2$) is a glass-ceramic material comprising 57%-80% SiO_2 and 11%-19% Li_2O, supplemented with various ceramic oxides and pigments [25]. It is commonly employed in single-unit restorations due to its favorable balance between mechanical strength and aesthetic properties [26]. Research demonstrates that lithium disilicate ceramics exhibit superior initial flexural strength and fatigue resistance, suggesting a longer clinical lifespan when subjected to typical masticatory forces [27].

Nevertheless, the material's inherent brittleness and high elastic modulus mismatch with dentin make lithium disilicate restorations susceptible to stress concentration at critical sites, thereby elevating the risk of catastrophic failure. Fatigue-induced fractures are predominantly characterized by "V-shaped" failures beneath the dentin-enamel junction, underscoring the role of stress accumulation in promoting fatigue-related damage [24][26].

Experimental investigations comparing occlusal thicknesses of lithium disilicate and zirconia crowns under varying loading conditions reveal that, while lithium disilicate crowns demonstrate higher survival probabilities under lower loads (~300 N), their reliability markedly diminishes under higher loads (600-900 N) [28]. This highlights the material's vulnerability to higher mechanical stresses and the need for optimal design considerations in clinical applications.Recent studies have shown that the preparation design of occlusal veneers significantly influences the fracture resistance of lithium disilicate ceramics. Taha and Hafez conducted in vitro experiments comparing the effects of two different preparation designs on the fracture strength of lithium disilicate/zronia-reinforced lithium silicate occlusal veneers [29]. The results indicated that lithium disilicate exhibited significantly higher fracture resistance. This improvement was attributed to axial reduction, which enhanced edge support and stress distribution, thereby optimizing the ceramic's fatigue resistance.

3.3 Novel CAD/CAM ceramic materials

The study of fatigue performance in novel CAD/CAM ceramic materials has provided new perspectives for clinical material selection. Abu-Izze et al. [30] compared ultra-thin restorations made from zirconia-reinforced lithium silicate (ZLS) and polymer-infiltrated ceramics (PIC). They found that PICs exhibited significantly superior fatigue life at a thickness of 0.5 mm, which was attributed to the ability of the polymer phase in PIC to inhibit crack propagation. Zheng et al. [31] further noted that while composite resin materials, such as Vita Enamic, exhibit lower fracture strength, their elastic modulus matches that of dentin, resulting in a higher repairable fracture ratio under cyclic loading. These materials are thus particularly suitable for high-load molar regions.

3.4 Conventional Resin Composites

Conventional resin composites consist of a resin matrix and fillers, such as SiO_2. Due to the differential thermal expansion coefficients between the fillers and the resin matrix, microcracks are prone to form under cyclic loading conditions [32]. Experimental studies involving cyclic impact loading (CIL) on various resin composite samples revealed that during loading, surface degradation occurs, and microcracks may form at contact points. These microcracks expand radially and connect with adjacent defects. As the number of loading cycles increases, these microcracks coalesce, leading to microfractures in the impact-loaded regions [33]. This behavior is likely associated with the mechanical properties of the polymer matrix. Additionally, the significantly higher modulus of the filler particles compared to the resin matrix may lead to the compression of the resin matrix during cyclic loading, resulting in localized cracking.

Lohbauer et al. pointed out that for resin-based composites, interfacial degradation during fatigue significantly influences crack propagation behavior, with the filler-matrix interface being the critical site of failure [34]. Drummond also noted that one of the reasons for the decline in the mechanical properties of dental composites in different aging environments is the hydrolysis and other changes occurring at the filler-matrix interface [35]. Other studies have found that water and other media can interact with the filler-matrix interface, further affecting its performance [36].

3.5 Glass Fiber-Reinforced Resin (FRC)

The fatigue performance of glass fiber-reinforced resin (FRC) has been a key research focus, demonstrating improved dynamic fatigue life compared to conventional resin materials. Under dynamic fatigue loading, a comparative study assessed the fracture resistance of maxillary complete dentures reinforced with glass fiber mesh and metal mesh [37]. The results indicated that dentures reinforced with glass fiber mesh exhibited higher fracture resistance than unreinforced dentures, though slightly lower than those reinforced with metal mesh. The incorporation of glass fibers effectively distributed stress and enhanced fracture resistance, suggesting a potential improvement in stress distribution within dentures. Although the fracture resistance of the glass fiber-reinforced group was lower than that of the metal-reinforced group, FRC dentures retained their overall structural integrity after failure, facilitating clinical repair [37].

However, the clinical application of FRC must account for the effects of prolonged exposure to humid and thermal conditions, which pose stability concerns at the fiber-resin interface. Studies indicate that in a humid and thermal environment, the fiber-resin interface is prone to hydrolysis, leading to a decline in fatigue strength [38]. Further research suggests that the chemical bonds at the fiber-resin interface in FRC are susceptible to water molecule infiltration, which weakens fiber-matrix adhesion and compromises interfacial integrity [39]. This increases the risk of interfacial debonding, highlighting the need for optimized interface treatment techniques to enhance long-term stability.

3.6 Resin-Based Composites

Resin-based composites have become the preferred direct restorative materials for both anterior and posterior teeth [40]. Research has demonstrated that self-healing resin-based composites containing microcapsules exhibit superior fatigue resistance compared to non-self-healing composites without microcapsules [41]. In indirect restorations, composite resin-based copings offer distinct advantages in failure patterns due to their elastic modulus being closely matched to that of dentin. A study by Altier et al. compared the fracture resistance of lithium disilicate copings with two types of microhybrid composite resin copings [42]. The findings revealed that the fracture load of the lithium disilicate group was significantly higher than that of the composite resin groups, while the repairable fracture ratio was notably higher in the composite resin groups. The elastic properties of composite resin facilitate stress dispersion, reducing the risk of root fractures. However, its lower fracture strength may limit its application in high-load areas such as the molar region [29][42][43]. This trade-off suggests that clinical material selection should be based on an individualized assessment of the patient's occlusal forces and aesthetic requirements.

3.7 Porcelain-Fused-to-Metal (PFM) Restorations

Porcelain-fused-to-metal (PFM) restorations, a widely used dental restorative material, consist of a metal substructure and a ceramic veneer. While the metal substructure provides high mechanical strength, PFM restorations remain susceptible to fatigue-related complications due to cyclic loading in the oral environment. Studies indicate that within a five-year observation period, PFM crowns exhibit various clinical complications, including open proximal contacts and porcelain chipping [43]. The failure mechanisms of PFM restorations are complex. One predominant failure mode is porcelain delamination. Due to the mismatch in the coefficients of thermal expansion between the metal and ceramic components, discrepancies in shrinkage occur during the high-temperature sintering and cooling processes, generating thermal stresses at the interface. When these stresses exceed the interfacial bond strength, the ceramic layer becomes prone to detachment. Additionally, fluctuations in oral temperature, chemical degradation, and repeated occlusal loading further weaken the adhesion between the ceramic and metal substructure, exacerbating the risk of veneer chipping. For instance, frequent consumption of excessively hot or cold foods induces thermal fatigue stress within PFM restorations, reducing interfacial integrity [44].

Another critical failure mechanism is metal fatigue fracture. Prolonged cyclic loading can induce microcrack formation within the metal substructure, which propagates over time, ultimately leading to structural failure. Additionally, PFM restorations may present clinical issues such as open proximal contacts and secondary caries, compromising their long-term performance. The prevalence of these failures varies across studies. A comparative analysis of PFM and all-ceramic restorations found that porcelain chipping was the most frequent failure mode in PFM restorations, along with marginal defects exposing the underlying metal framework [45].

3.8 Material Processing and Interface Optimization Techniques

3.8.1 AI-Driven Crown Design

Artificial intelligence (AI) has introduced innovative approaches for personalized dental crown design. Ding et al. developed an AI algorithm based on a 3D deep convolutional generative adversarial network (3D-DCGAN) [46], trained on 600 sets of natural dentition data to generate crowns that closely match the morphology and biomechanical properties of natural teeth. The results indicated that AI-designed crowns exhibited significantly lower morphological deviation compared to CEREC Biogenetic designs and manually crafted crowns. Moreover, the number of occlusal contact points in AI-designed crowns was statistically comparable to those of natural teeth. Finite element analysis further revealed that under a 300 N load, the stress distribution of AI-generated crowns closely resembled that of natural teeth, with fatigue life predictions outperforming conventional designs [56]. This technology enhances occlusal morphology and stress distribution, mitigating biomechanical inconsistencies introduced by subjective factors in traditional CAD/CAM crown designs.

3.8.2 Surface Roughness Optimization in Zirconia CAD/CAM Manufacturing

In the application of CAD/CAM technology for dental zirconia processing, cutting parameters particularly cutting speed and tool wear directly influence surface roughness [45]. Surface roughness significantly affects the fatigue performance of zirconia by influencing stress concentration, corrosion susceptibility, and crack propagation. Studies have demonstrated that factors such as cutting speed, feed rate, and cutting depth all impact surface roughness [47][48][49]. Selecting optimal cutting parameters and tools can effectively reduce surface roughness and enhance material performance. Experimental findings indicate that at a cutting speed of 150 m/min, a feed rate of 0.05 mm/z, and cutting depths of 0.1–0.2 mm, all measured surface roughness values remained below 0.2 µm, meeting the clinical requirements for dental applications [50]. Therefore, selecting appropriate cutting parameters during zirconia CAD/CAM processing is crucial for optimizing material properties.

3.8.3 Titanium Base Integration for Fatigue Resistance in Implant Abutments

Recent advancements have demonstrated that titanium bases significantly enhance the fatigue resistance of zirconia and lithium disilicate implant abutments. In a simulated five-year fatigue study (1,200,000 cyclic loads), Elsayed et al. found that zirconia abutments without a titanium base (Zr group) were highly prone to fracture under dynamic loading, with a median fracture load of only 198 N far below the physiological occlusal force range (150–235 N). In contrast, zirconia and lithium disilicate abutments with titanium bases exhibited no ceramic fractures or debonding, with fracture loads reaching 944 N and 970–980 N, respectively [51]. The incorporation of titanium bases effectively disperses stress concentrations and enhances interfacial stability, significantly improving the fatigue resistance of zirconia and lithium disilicate, particularly under high-load conditions. This prevents common failure modes such as grain boundary fractures and marginal chipping [20][24][51]. Additionally, adhesive bonding techniques, such as sandblasting and resin-based luting agents, further optimize interface adhesion, reducing the risk of microcrack propagation [52]. These findings suggest that the introduction of titanium bases mitigates the mechanical limitations of zirconia and lithium disilicate, providing a more reliable solution for implant-supported restorations in esthetic zones.

3.9 Evaluation Method

3.9.1 Thermomechanical Aging Models

Thermomechanical aging models are widely used to simulate the oral environment and assess their impact on the performance of dental materials. Researchers have employed thermal cycling to replicate intraoral conditions and evaluate the bonding strength of various adhesives to zirconia ceramics. Results indicate that thermal cycling affects the bonding strength of all tested adhesives except for two (Panavia series and Rely X Unicem) [53], suggesting that thermomechanical aging alters the adhesive-ceramic interface properties. Additionally, the influence of thermomechanical aging on bond strength varies depending on the material combination. Conventional resin adhesives, such as Panavia V5, exhibited significantly higher bond strength after accelerated thermomechanical aging compared to self-adhesive, self-etching adhesives, and substantial differences were observed across different ceramic-adhesive combinations [54].

3.9.2 Mechanical Loading in Laboratory Simulations

When applying mechanical loads in laboratory settings, the selected force should approximate masticatory forces to enhance the reliability of test results. A review of the literature reveals that a 50 N load is the most frequently chosen value to simulate chewing forces in numerous scientific studies [55][56]. In laboratory conditions, mechanical loading is typically achieved through the use of dead weights, which offer the advantage of providing a constant and controlled force throughout the entire masticatory cycle. For instance, applying a weight of approximately 5 kg can generate a chewing force of 50 N, effectively replicating physiological loading conditions [57].

4. SCENARIO ANALYSIS

Despite significant advancements in understanding fatigue mechanisms and optimizing dental restorative materials, several challenges persist. Laboratory studies often employ constant loads to simulate occlusal forces, failing to replicate the dynamic nature of the oral environment, including variations in chewing frequency and temperature fluctuations. This discrepancy can lead to biased performance assessments. Additionally, long-term clinical data remain scarce, particularly for novel materials such as high-translucency zirconia and self-healing resins, with limited follow-up studies exceeding five years. Challenges also exist in optimizing material interfaces, as bonding strength between titanium bases and ceramics is highly dependent on surface treatments, necessitating the development of more stable interfacial bonding techniques. Furthermore, the long-term stability of fiber-resin interfaces under humid thermal conditions remains unresolved, requiring innovative solutions.

Future research should focus on multiscale modeling, integrating finite element analysis with molecular dynamics to better understand how microscopic defects influence macroscopic fatigue behavior. Intelligent material development, leveraging machine learning, offers potential for predicting fatigue lifespan and optimizing composition and processing parameters. Additionally, the establishment of coupled dynamic environment testing incorporating mechanical loading, chemical degradation, and microbial activity will provide more clinically relevant fatigue evaluation systems. Through interdisciplinary collaboration and technological innovation, dental restorative materials are expected to achieve significant improvements in fatigue resistance and clinical adaptability, ultimately enhancing durability and reliability in patient care.

5. CONCLUSION

Understanding the fatigue performance and failure mechanisms of dental restorative materials under dynamic occlusal forces is crucial for improving their clinical longevity. This study systematically compares various materials, highlighting their strengths, limitations, and potential optimization strategies. Zirconia demonstrates high flexural strength and fracture toughness but is susceptible to phase transformation and grain boundary fractures, which can be mitigated through titanium reinforcement and surface treatments. Lithium disilicate offers superior aesthetics but suffers from stress concentration due to elastic modulus mismatch, necessitating optimized preparation designs for enhanced fatigue resistance. Resin-based materials are prone to interfacial degradation in humid thermal environments, where self-healing technologies and fiber reinforcements show promise. Meanwhile, porcelain-fused-to-metal (PFM) restorations experience both porcelain delamination and metal fatigue failure under prolonged cyclic loading, requiring advancements in interface optimization and bonding techniques.

Technological advancements further improve material performance. AI-driven crown design using 3D-DCGAN significantly reduces stress concentration by optimizing morphology. CAD/CAM processing parameter refinement, such as a cutting speed of 150 m/min, minimizes surface roughness and delays crack initiation. Additionally, titanium-based implant technology enhances the fracture load capacity of zirconia and lithium disilicate abutments beyond physiological occlusal forces (>900 N). However, current evaluation methods, such as ISO 14801, fail to account for multidirectional dynamic loading, underscoring the need for more clinically relevant fatigue testing models.

Conflict of Interest

The author declare no conflict of interest

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