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WEAR IN RESTORATIVE DENTISTRY/TEETH AND DENTAL MATERIALS

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Abstract: *Wear is a significant concern for dental tissues exposed to abrasion, attrition, and erosion, as well as for dental materials that must have sufficiently wear-resistance without causing harm to the opposing teeth. In addition, an ideal restorative dental material should have wear properties similar to those of the tooth tissues. Both clinical and experimental findings indicate that wear mechanisms typically do not act independently, but interact with one another. Various materials and techniques for rehabilitating worn teeth have been discussed in the recent literature. There are also some data available on the clinical performance of restorations used in treating tooth wear. Therefore, this paper presents a comprehensive review of wear phenomena in restorative dentistry, emphasizing the multifactorial mechanisms—abrasion, attrition, erosion, abfraction, fatigue, and adhesive wear—that contribute to the degradation of both natural teeth and restorative materials. It explores the clinical significance of tooth wear, material-specific wear behavior, and testing methodologies such as in-vivo observations and in-vitro simulations including jaw and chewing simulators, tribological tests, and advanced surface analysis techniques. The study also discusses preventive strategies, clinical decision-making, and the future direction of restorative dentistry, highlighting innovations in biomaterials, digital technologies, and personalized treatment approaches aimed at minimizing wear and enhancing patient outcomes.*

Keywords: Wear in Dentistry, Wear Mechanisms in Dentistry, Dental restorative materials, Dental Wear Test Techniques

1. INTRODUCTION

Wear in dentistry is a critical phenomenon that affects the longevity and function of restorative materials as well as natural teeth. Wear is a term used to describe the progressive loss of material from a surface owing to mechanical action, natural aging, environmental influences, and habits [1]. Wear occurs when dental materials or natural tooth surfaces undergo abrasion, attrition, or erosion because of interactions with opposing surfaces, food, or other environmental factors [2]. The impact of wear is significant, as it can lead to compromised aesthetics, impaired function, challenges with effective phonetics and mastication, pain, discomfort, and even failure of restorative treatments [3]. Wear can affect various dental materials, including metals, ceramics, composites, and natural tooth enamel, each of which may have specific wear characteristics [4].

Understanding wear mechanisms and preventing or mitigating their effects are crucial for optimizing dental care. Many papers have been published on the wear of dental materials and/or natural teeth. In addition, review and overview papers have also been published to clarify the studies on dental wear and provide a clear perspective to scientists and practitioners on this critical issue of dental care. However, there are still gaps in this subject, and it is important to reconsider the subject of wear in dentistry with the development of scientific knowledge and new approaches. This review emphasizes the clinical importance of wear, specifically concerning natural teeth and restorative materials, as well as the laboratory techniques used to replicate the wear of these restorative materials.

2. WEAR IN NATURAL TEETH/RESTORATIVE MATERIALS

Dental enamel exhibits significant resistance to wear, with an average annual vertical loss of approximately 20–30 µm in the posterior teeth. The rate of enamel wear is notably elevated during the initial two years following contact with opposing teeth, a period referred to as the running-in phase, after which the rate diminishes. Enamel wear primarily occurs due to microfracturing and is marked by delamination and microploughing, whereas dentine wear is characterized by the formation of ductile chips [5].

In dentistry, tooth wear is to the gradual loss of mineralized tooth tissue resulting from physical or chemical-physical processes, and it is not associated with dental caries [6, 7]. The occurrence of wear may stem from various mechanisms such as erosion, attrition, abrasion, and possibly dental abfraction, which can happen either independently or in conjunction with one another. These mechanisms may be triggered by exposure to acids of non-bacterial origin, as well as non-physiological mechanical forces resulting from tooth brushing, malocclusion, and parafunctional activities.

Wear mechanisms refer to the processes that contribute to the gradual loss or degradation of dental materials and tooth structure over time due to mechanical, chemical or biological factors [8]. It is important to understand these mechanisms because they affect the longevity and functionality of dental restorations and natural teeth [2]. There are several types of wear mechanisms in the natural teeth and dental materials as outlined below. Each of these mechanisms contributes to the overall wear of teeth or dental materials and influences the choice of materials used in dentistry as well as the techniques for maintaining oral health [2,9].

Attrition: Attrition is the wear of mineralized tooth or restoration surfaces because of direct contact with opposing surfaces during mastication [6,10]. It mainly occurs when natural teeth grind against each other or against dental restorations. While some degree of attrition is a natural part of aging, excessive wear caused by bruxism (teeth grinding) or malocclusion can accelerate the process, leading to increased tooth sensitivity, changes in bite, and other issues. Clinically, attrition-induced wear on the teeth results in wear patterns on opposing teeth. In the early stages, there may be small, shiny areas on cusp tips or slight flattening of the incisal edges, while severe attrition can expose the dentin, potentially speeding up the wear process [11]. The other clinical signs are tooth fractures – natural teeth or restorations, tooth mobility, pulpal necrosis, traumatic ulcers and masticatory muscle hypertrophy [11,12]. Symptoms of attrition include nocturnal teeth grinding, jaw discomfort, fatigue, restricted mouth opening upon waking, a sensation of loose teeth, tenderness in the teeth or gums, headaches in the temporal area, and the grinding or clenching of teeth while awake [12]. Fig. 1(a)-(b) show tooth attrition because of tooth-to-tooth contact and it caused decreased vertical dimensions and esthetics. Fig. 1(c) shows the effect of ceramic prosthesis caused attrition on opposite teeth. Fig. 1(d) shows the occlusal and incisal surfaces of worn teeth because of attrition.

Figure 1. (a)-(b) Tooth-to-tooth contact results in attrition and decreases the vertical dimensions of teeth [12]. (c) In a 73-year-old patient, ceramic prostheses in the maxilla caused attrition on opposite natural teeth. (d) A 66-year-old female patient having dental attrition on occlusal surfaces of the mandible

Abrasion: Abrasive wear refers to the loss of material from the surface due to the mechanical action of harder materials scraping against softer surfaces. In dentistry, abrasion is commonly caused by external factors such as abrasive toothpaste, hard bristles, and a vigorous brushing technique. It may also be seen by the use of toothpicks and miswaks, as well as the consumption of abrasive foods. For restorative materials, abrasion can significantly affect the lifespan of restorations, especially in regions with high occlusal forces like posterior teeth [13]. The other factors may be chewing nuts, pens, pica, pipe smoking, eating stone-ground bread, eating unwashed food with sand, using teeth as tools.

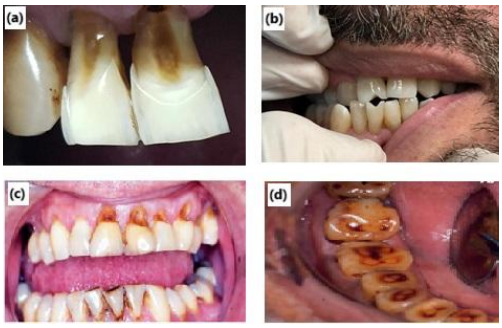

Figure 2. (a) A typical abrasive wear as a result of using miswak [13]. (b) Abrasion lesions caused by the consumption of dried sunflower seeds [13]. (c) Abrasion on the left side of teeth showing that inappropriate force and brushing technique with the right hand [14]. (d) Abrasion lesions because of chewing betel nuts [14]

Some typical examples for abrasion are shown in Fig. 2(a)-(d) [14]. In Fig 2(a), wide abrasion lesions occurred because of using miswak. Fig 2(b) shows the abrasive wear on the incisal surfaces because of the consumption of dried sunflower seeds. Fig 2(c) represents the abrasion lesions because of inappropriate brushing technique. The effect of chewing betel nuts on the occlusal surfaces of posterior teeth is shown Fig 2(d).

Erosion and corrosive wear: Erosion refers to the chemical degradation of material from a surface caused by acid exposure. This can occur internally, as a result of gastric acid or externally, due to acids from dietary sources, environmental factors, or occupational hazards (referred to as extrinsic or exogenous erosion) [6,15,16,17]. The acids which are from moderate (approximately pH = 5) to strong (pH = 1.2) act on tooth surfaces over short periods (15-60 s) and cause erosion. In dentistry, erosion typically affects enamel and can lead to significant loss of tooth structure, especially in individuals with acid reflux, frequent consumption of acidic foods or drinks, or those who suffer from eating disorders. Some erosive wear types were shown in Fig. 3(a)-(d) [18]. In Fig 3(a), an example of cervical erosion lesions on anterior teeth caused by drinking diet cola and holding it in the muco-buccal fold were presented. In Fig 3(b), patient with palatal erosion lesions due to gastroesophageal reflux were shown. Palatal erosion resembling pattern seen with bulimia nervosa in a patient who drinks five glasses of champagne per night is shown in Fig. 3(c). In Fig 3(d), examples of dental composite and amalgam restorations standing proud in teeth with erosive wear were shown.

Corrosive wear may affect both the metal alloys, dental amalgam, gold and composite materials used in dentistry. For instance, metals may corrode due to exposure to acidic conditions, and composite materials may degrade as a result of chemical reactions with saliva or food. The material may lose its strength, functionality, and aesthetic appearance because of corrosion. The oral cavity is a catalyst for corrosion. It remains consistently moist and frequently experiences fluctuations in temperature. The consumed foods and beverages exhibit a broad spectrum of pH levels [19].

Figure 3. (a) Cervical erosion lesions on anterior teeth caused by drinking diet cola and holding it in the muco-buccal fold were presented. (b) Patient with palatal erosion lesions due to gastroesophageal reflux were shown. (c) Palatal erosion of patient who drinks five glasses of champagne per night. (d) Restorations with dental composite and amalgam standing proud on teeth with erosive wear [18]

Abfraction: Abfraction refers to the loss of tooth structure along gingival margin, presenting in various clinical forms [20]. These lesions occur in both dentine and enamel of the tooth frequently around the cervical areas [21]. It has a multifactorial origin and can result from both regular and irregular tooth function, often accompanied by pathological wear like abrasion and erosion [22,23]. It is based on the relationship between stress concentration and occlusal loading in the cervical region of tooth and frequently seen on the buccal surfaces of the teeth [22]. In normal occlusion, occlusal stresses are directed towards the apical area of the tooth. However, in the case of premature contacts, bruxism, clenching, and malocclusions, these stresses are directed in the lateral direction towards the cervical area. Then, they cause tooth cusp flexure resulting in the collection of stresses at cervical area. These stresses cause fracture and breakdown of hydroxyapatite bonds in enamel [24,25]. Abfraction lesions generally appear in three shapes as either wedge, saucer or mixed patterns [26]. Wedge and saucer shaped lesions are the most common, while mixed lesions are less frequently identified in the oral cavity. In Fig.4, wedge-shaped lesions have the sharpest internal line angles, while saucer or mixed-shaped lesions may present either a smooth internal surface or a range of variations [26].

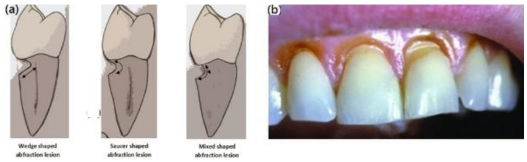

Figure 4. (a) The forming mechanism of abfraction and (b) its clinical example [20,26]

Fatigue wear: Fatigue wear in dentistry refers to the gradual deterioration or damage of dental materials due to repeated mechanical stress or load over time. This wear is similar to the concept of metal fatigue in engineering, where materials weaken after being subjected to repeated cycles of stress. In the context of dentistry, fatigue wear can occur when a dental restoration is subjected to the continuous forces from chewing, biting, and grinding. These repetitive forces can cause tiny fractures, cracks, or surface wear on dental materials, which may lead to the failure of the restoration over time. Common dental materials like composite resins, ceramics, or metals are all susceptible to some degree of fatigue wear, though different materials behave differently under stress. Fig.5. shows the typical fatigue wear of enamel in an 82 year-old male [15].

Figure 5. Fatigue wear of enamel in an 82 year-old male who had an oral habit [15]

Adhesive wear: Adhesive wear is the unexpected transfer of material compounds and wear debris from one surface to another when the surfaces are in frictional contact [7]. This process, primarily observed in metal and composite restorations, takes place when two surfaces experience significant pressure and move against one another. From a tribological perspective, the surface irregularities that come into contact can undergo plastic deformation, leading to localized bonding in certain areas through a mechanism similar to cold welding [15]. Actually, in-vitro two-body friction tests have demonstrated a transfer of material to enamel (or an analog of enamel) from restorative materials like amalgam, gold, and some composites under high pressure [27, 28, 29].

On the other hand, the choice of material for dental restorations is a critical factor in managing wear. Several materials, which are commonly used, have distinct wear characteristics.

Metals: The essential importance of metallic materials, including gold, silver, copper, and alloys such as cobalt-chromium and titanium, is emphasized due to their exceptional mechanical properties in dental restorations. These properties encompass a high elastic modulus, tensile strength, hardness, and wear resistance [30]. Gold, in particular, is highly resistant to wear and causes minimal wear to opposing teeth. However, metals may not always provide the best aesthetic outcomes and are often used for posterior restorations.

Ceramics: Dental ceramics are generally harder than human tooth enamel and metal alloys [31]. The hardness of three types of dental ceramic materials—zirconia, lithium disilicate glass ceramic, and dental porcelain—varies between 492 ± 16 Hv and 1287 ± 33 Hv, which is considerably greater than the hardness of bovine tooth enamel, measured at 303 ± 14 Hv. Furthermore, bovine teeth are utilized as abrader and substrate specimens due to the similarity in hardness between human tooth enamel, which ranges from approximately 274 to 317 Hv, and bovine tooth enamel, which is around 300 to 340 Hv [32,33,34]. In a study which was evaluated the wear of the antagonist tooth in ceramic restorations, it was found that feldspathic produces greater wear of the antagonist tooth from ceramic restorations linearly and volumetrically [35]. In addition, zirconia generates the least wear that will decrease over time, and it will be equal to or less than the natural wear in the tooth.

Composites: Composite resins offer excellent aesthetics and moderate wear resistance. They are commonly used in anterior and posterior restorations [36]. While composites are less wear-resistant than metals or ceramics, advancements in composite formulations have improved their durability. However, composites can wear over time, especially under heavy occlusal forces. [37]. Despite progress in resin technology, the adverse differential wear of direct resin composites when in contact with opposing teeth and restorative materials continues to be a significant issue, especially for patients experiencing wear. For this reason, it was suggested that a reasonable service period of such restorations to be in the range of three to five years [38,39].

3. WEAR TEST TECHNIQUES IN DENTISTRY

Wear test techniques in dentistry are crucial for evaluating the performance of restorative materials such as crowns, bridges, and fillings under conditions that mimic real-life wear. These tests help to assess the durability, wear resistance, and ability of the material to maintain its shape and function over time. By using these techniques, dental researchers can gather valuable data on the longevity, performance, and safety of different restorative materials, which help to guide the selection of appropriate materials for specific clinical situations [40]. Wear of hard dental tissues and dental reconstructions can be measured as in-vivo or in-vitro. It is important to recognize that relying solely on laboratory or clinical tests is not feasible; rather, a combination of both is essential.

Many in-vitro laboratory test methods have been developed by researchers in the literature [41,42,43,44]. These devices have been created under laboratory conditions for the testing of hard dental tissues and materials used in restorative dentistry. Their aim was to imitate the conditions that exist in the mouth as much as possible and to maintain the definability of the testing conditions [40]. Most of the devices are used for two-body wear test, which simulates the contact of teeth without the presence of third-body like food. However, food components are also important that control the wear mechanisms depending on their hardness during the chewing [45]. Therefore, some devices have been already adapted to add foods as a third body to simulate well the chewing system.

3.1 Clinical patient-based (in-vivo) evaluation and monitoring techniques of wear

These techniques in restorative dentistry involve evaluating the performance of dental materials in real-life conditions inside a patient's mouth over time. These techniques are important for assessing the long-term durability, functionality, and aesthetic stability of restorative materials such as crowns, fillings, and veneers [46]. Unlike laboratory tests, which simulate wear conditions under controlled environments, clinical wear evaluations focus on observing how materials behave in the natural, dynamic conditions of the oral cavity. Many approaches and techniques have been developed for evaluating or monitoring the wear inside a patient's mouth over time.

Qualitative methods: The dentist examines the restorations for visible signs of wear, including surface abrasions, cracks, chipping, discoloration, or loss of structural integrity. The predominant approach for evaluating dental wear involves the application of quality indices that utilize numerical scoring systems to evaluate the advancement of the assessed condition. These qualitative techniques yield subjective descriptive information, and evaluators can perform assessments without the need for specialized monitoring tools, relying instead on direct visual inspection of the lesions. While these data are valuable for epidemiological research, comparing results can be challenging due to the absence of standardization among evaluators [47,48]. Therefore, these types of indices are characterised by a subjective component and are developed without considering the etiological factors that cause dental wear on the surfaces [49].

Quantitative methods: These techniques yield more objective data; however, their application is more challenging due to the necessity of working casts and laboratory technologies that are not readily available. Furthermore, they are less convenient for clinicians when it comes to identifying lesions and evaluating their progression in a dental clinic setting [50]. Clinically, the measurement of quantitative height loss in teeth and restorations over time can be achieved through digital impressions and direct superimposition, or by utilizing analog impressions to examine the resulting gypsum or acrylic casts [51]. Quantitative methods include a variety of techniques, such as ultrasonic measurement, the development of predictive models, scanning electron microscopy (SEM), the application of polarized imaging lasers, 3D laser confocal microscopy, optical coherence tomography, profilometry, colorimetry for assessing surface loss, and the utilization of intraoral or extraoral scanners [50]. The techniques such as intraoral cameras and digital scanners may be used to monitor the surface of restorations more precisely, capturing subtle changes in shape or texture [52]. Future perspectives for clinical wear measurement include the evolution of intraoral scanners, which should avoid the use of replicas and improve final accuracy and precision [53].

3.2 In-vitro (laboratory) wear test techniques

Many devices have been developed for the wear testing of hard dental tissues and dental materials under laboratory conditions [54]. Their aim is to imitate the conditions that exist in the mouth as much as possible and to maintain the definability of the testing conditions [40]. Most of the devices are used for two-body wear test. However, this only simulates the contact of teeth without the presence of food. During chewing, food components depending on their hardness are important for wear mechanism. Consequently, certain testers have already been modified to incorporate a third component, which is the food sample for wear tests [40].

Simulated mastication tests
These tests involve using mechanical simulators that replicate chewing motions to simulate long-term oral function. Materials are subjected to repeated cycles of chewing forces, which can simulate years of wear within weeks or months [55,56].

Jaws simulators: They typically refer to dental simulation models designed to mimic the human mouth, jaw, and teeth [40]. These simulators are used for educational, training, and practice purposes, particularly for dental students, professionals, or researchers. Jaws simulator consists of a model of the upper and lower teeth that are moved towards each other by two or more servo-hydraulic motors [57]. The first motor facilitates movement along the vertical axis, while the second motor enables movement along the horizontal axis. Both motors are controlled by a computer to precisely mimic the physiological movements associated with chewing. Users can customize the bite strength and the number of cycles. Additionally, the device includes an artificial oral environment. This includes the possibility of temperature setting, as in the human body. Artificial saliva and/or food samples can also be added for a more realistic simulation.

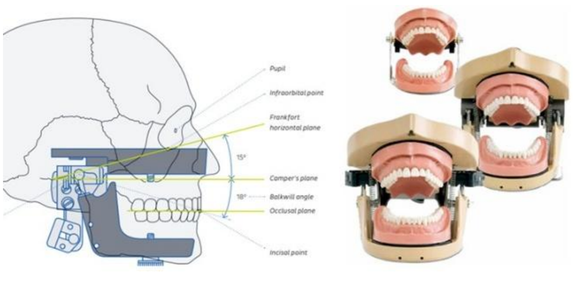

Figure 6. Jaw simulators [58]

Chewing simulators: A chewing simulator is used to conduct in-vitro wear and fatigue tests on teeth, implants and composite restorative materials made from polymers, ceramics, and similar materials [59]. It can be used in in-depth analyses of the following features [60]:

- Dental material wear resistance,
- Implant surface durability,
- Comparative analysis of filling materials,
- Restorative materials lifespan,
- Denture teeth wear analysis,
- Effect of food consistency on teeth.

It can conduct two-body and three-body abrasive wear and thermal fatigue on teeth, tooth implants, and composite restorative materials. The chewing simulators may have different modes such as cyclic, wear and chewing. Wear parameters of chewing force, tooth sliding distance, thermal change, food abrasiveness, saliva lubrication, and behavior of antagonist materials can be investigated [60, 61]. The simulator can accommodate many samples at a time with the ability of different loading weights. Antagonists are changeable including rounded, flat and pointed end rods [60]. Fig. 7(a)-(c). shows the schematic and real views of chewing simulator.

Figure 7. (a) Schematics of the dual-axis of sliding wear simulation test mechanism for in-vitro laboratory chewing cycle test simulation [62]. (b)-(c) A chewing simulator with multiple testing stations with a detailed single station [63]

ACTA Wear Simulators: The ACTA-Method has been developed at the Dental College in Amsterdam (The Netherlands) (ACTA = Academisch Centrum Tandheelkunde Amsterdam) [64]. It plays a crucial role in the field of restorative dentistry by providing a controlled and reproducible environment to test and evaluate the performance of dental materials under conditions that mimic natural chewing [64]. It helps in understanding how dental materials respond to mechanical and environmental stresses, thus contributing to innovations in restorative materials and techniques.

The simulator was designed to replicate the physical forces and movements that occur in the human mouth during mastication, allowing for controlled wear testing of dental materials such as fillings, crowns, and other restorations [65]. The test samples are positioned around the edge of one wheel, while the opposing wheel acts as the antagonist (Fig. 8). The force exerted when the two wheels meet is set to 15 N. Both wheels are immersed in a slurry composed of white millet seeds mixed with a buffer solution. After completing 50,000, 100,000, and 200,000 cycles, the maximum vertical displacement of the test specimens was recorded using a profilometry device.

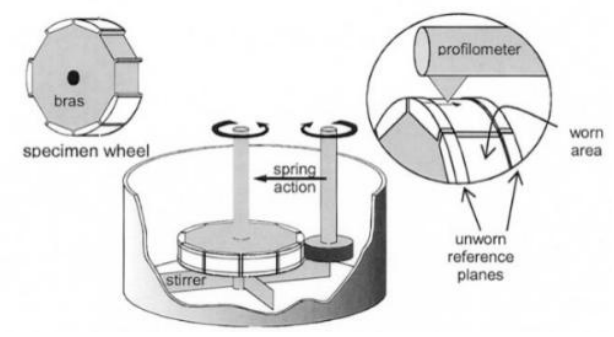

Figure 8. Schematic illustration of ACTA wear simulator (Academic Center for Dentistry Amsterdam (ACTA)) [64]

Abrasion testing

Toothbrush abrasion tests: The wear of hard dental tissues and dental materials occur not only during chewing of food, but also during tooth brushing. The size of such wear in patients depends on many factors, like toothbrushing technique and frequency, hardness of toothbrush bristles, dexterity of the patient and also toothpaste used [40, 66]. Toothbrush abrasion testers simulate tooth brushing to assess the wear of restorative materials under simulated conditions of regular brushing [67,68,69]. This method uses a toothbrush which cyclically linearly moves on the surface of tested material with the adjustable pressure force [70]. Standardization of this test is important not only with regard to the device, but also to the selected toothbrush. It is possible to add a third component of wear – toothpaste or only abrasive particles of toothpaste for a true simulation.

Abrasive slurry tests: The abrasive slurry test in dentistry is a laboratory test used to evaluate the wear resistance and durability of dental materials, particularly those used in restorations such as composites, ceramics, and dental cements. In this test, a slurry made of abrasive particles (often containing a mixture of water and pumice or other fine abrasives) is used to simulate the mechanical wear that dental materials might experience in the oral environment. A slurry (containing particles such as toothpaste) is used to test how well a material resists abrasive forces over time [73, 74].

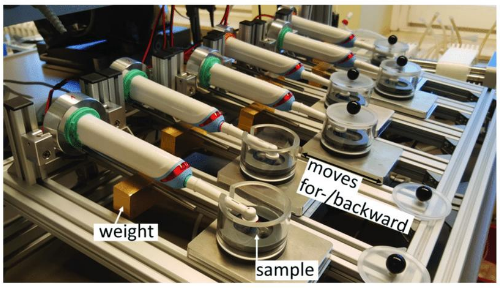

Figure 9. A lateral view of the tooth brushing simulation device [71,72]

Tribological tests

These tests evaluate friction and wear and related subjects between the restorative material and the opposing tooth or material [75]. Common methods include pin-on-disk/ball-on-disk tests (in macro-scale), scratch tests (in micro-scale) and micro-/nano-indentation tests (in micro-/nano-scales).

Pin-on-disc/Ball-on-disc tests: The pin-on-disc type tribometers are commonly used for evaluating the friction behavior and wear resistance of materials used in different applications where tribological actions are operative. This test is preferred because of its simplicity, standardization and cost efficiency. This test technique has some limitations regarding the applications of dentistry. The test device does not accurately replicate conditions in the oral cavity, which is a critical factor when studying wear in dental materials. Another problem is that the test device differs significantly from conditions in the oral cavity [57]. However, it is possible to adjust various parameters, such as pressing force, rotational speed, and number of cycles to adapt to oral conditions. It is also possible to include third component of wear-abrasive food particles in distilled water or in artificial saliva to make a more realistic test conditions for chewing [45].

Scratch test: A scratch is made on the tooth surface with a scalpel blade in this technique. The scratch disappearing or diminishing in time is an indication that erosion has occurred. Serial colour photographs can also be used to compare changes in enamel translucency and shade of the affected enamel. It is possible to view the scratch in the sample in great detail and identify the violations of its borders, its depth and influence of the material homogeneity on the test with microscopic imaging like confocal laser scanning microscope. In the scratch test, three distinct types of cracks can be identified as they develop from both the surface and subsurface: radial cracks, median cracks, and lateral cracks. Crack propagation reduces the strength of the material [77]. Two examples of scracthes formed during scratch tests are shown in Fig. 11 for amalgam and composite materials used in restorative dentistry.

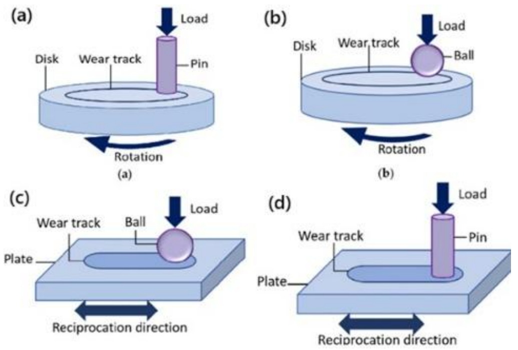

Figure 10. The main test configurations for a common tribometer: (a) Pin-on-disk, (b) ball-on-disk, (c) ball-on plate, and (d) pin-on-plate [76]

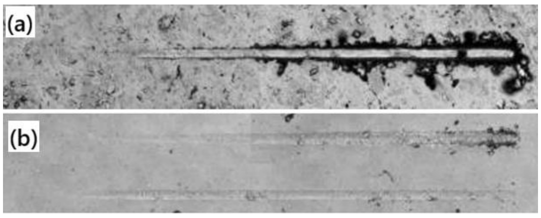

Figure 11. Examples of scratch test results for two materials used in restorative dentistry: (a) Amalgam and (b) composite materials [40]

Micro-/Nano-indentation tests: There are two scales for this test: Micro- and nano-indentation. After nanofillers usage, the terms microhardness and nanohardness have been introduced in operative dentistry. A nanoindenter measures the hardness and elastic modulus of a material on an extremely smaller surface scale of 50 nm [78]. Nanohardness is generally defined as a material's resistance to permanent or plastic deformation at the nano-micro level. This test focuses on research of the materials physical properties, which are related to the rate of wear [40]. These tests apply a controlled force to a material and measure the resulting indentation to assess its hardness and wear resistance. The test is realized by pressuring of diamond tip with a defined shape into the sample materials. The advantage is the testing of small samples without their destruction. However, the test is sensitive to the sample homogeneity and surface roughness. Therefore, within one sample, several indentations are made and they are consequently separately evaluated [79,80]. Measuring hardness and elastic modulus is presently the most effective method for comparing dental materials and prediction their wear rate.

3.3 Secondary investigation/characterization techniques after wear tests

In the context of dental materials, secondary investigation or characterization techniques are used to analyze the wear properties/performance of dental materials following simulated wear tests. These tests help evaluating the material’s durability, wear resistance, and overall behavior under oral conditions. These techniques provide in-depth information about the effects of wear on dental materials, allowing researchers and clinicians to make better-informed decisions about material performance, longevity, and suitability for clinical use.

Scanning electron microscopy (SEM): SEM is a crucial dental tool for examining composite surface properties before and after wear tests. SEM uses a narrow beam of electrons, only 10 nanometers thick, to scan the surface. SEM provides detailed images of the surface to observe cracks, wear patterns, and structural degradation. It helps to visualize any microstructural changes, such as crack formation, wear types, and the presence of any debris on the material surface. SEM examination provides valuable insights that significantly improve our understanding of composite resin materials and optimize their performance in dental applications [81]. After testing, the surfaces of the restorations can be examined under high magnification with SEM to detect wear patterns, surface roughness, and damage. This helps determine the type of wear that the material experienced during testing [82].

Energy dispersive X-ray spectroscopy (EDX or EDS): EDS or EDX coupled with SEM analyzes the elemental makeup of the wear surfaces or any particles generated during the wear test. It can help detect the release of materials, identify wear particles, and assess any surface contamination or material degradation. In EDX analysis, an electron beam is directed across the sample to create an image representing the elemental composition. This technique allows for the measurement of the composition and concentration of heavy metal ions present in nanoparticles located at or near the surface of the sample. However, elements with atomic numbers lower than 11 are challenging to detect using EDX [83].

X-ray diffraction (XRD): XRD analyzes the diffraction patterns of X-rays interacting with the material's crystalline structure. The XRD examines any crystallographic changes in the material after wear tests. It helps identify phase changes in the material that might affect its wear resistance.

Fourier-transform infrared spectroscopy (FTIR): FTIR detects the absorption of infrared light by the material's molecular bonds and provides information on chemical changes after wear. It helps identify any chemical degradation, oxidation, or polymerization changes that may have occurred during wear testing.

Atomic force microscopy (AFM): The AFM is used to measure the surface topography at a nanometer scale after wear. It scans the surface of the sample using an extremely thin lever or tip, typically with a diameter in the range of 40 to 60 nm [84]. This provides a comprehensive understanding of the topography and irregularities of dental composites. This, in turn, facilitates the development of dental composite formulations to achieve optimal clinical outcomes [85]. The AFM gives a very high-resolution image of the surface, allowing for detailed analysis of microscopic wear.

Wear debris investigations: In several disciplines, attention is payed to the impact of wear debris. This is addressed in dental in-vitro wear studies [86,87]. Wear debris in dentistry refers to tiny particles or fragments of material that are generated when dental materials, such as crowns, fillings, or artificial joints, undergo mechanical wear during normal use. Debris in dentistry is examined using some sophisticated tools like SEM and XRD, which give some valuable information about the wear mechanisms operated.

Hardness testing: It is important to evaluate the hardness of the material before and after wear tests. A microhardness indenter is used to apply a small force to the material's surface and measure the indentation depth. Hardness is a key indicator of wear resistance. Changes in microhardness can reveal how the material's surface properties have altered due to wear [45,80].

Surface profilometry: Achieving polished surfaces on dental restorations is crucial for health, oral comfort and cosmetic considerations [88]. The primary goal of finishing and polishing procedures is to ensure that restorations have a proper shape, are properly aligned, and have a smooth surface that promotes the maintenance of healthy gingival margins. [57]. Profilometric investigation is used to measure the wear and topographical changes on the material surface after wear tests [84]. This technique uses a stylus or optical method to measure the surface roughness, depth of wear, and any material loss. It helps assess how the material surface has changed after wear and whether it is still suitable for long-term use [45].

Optical profilometers: Surface topography refers to the three-dimensional features of a surface that can be analyzed and displayed using optical profilometers [81]. These devices provide a non-contact approach to obtaining 3D measurements of a surface.

Mechanic profilometers: Designed specifically for two-dimensional measurements, the mechanical profilometers work by systemically scanning the surface with a diamond tip that maintains a constant linear distance from the sample surface. These profilometers use a diamond tip to scan the sensors horizontally with a resolution between 20 and 50 µm [89].

4 STRATEGIES FOR MINIMAZING WEAR

4.1. Assessment of risk factors of wear

The degree and speed of wear are influenced by the severity of tooth grinding (attrition), exposure to dietary and stomach acids (erosion), and improper tooth brushing or the use of abrasive toothpaste (abrasion). It is pronounced when multiple primary causes and contributing factors are present, such as reduced saliva production, abrasive dental materials, defective tooth structure, and insufficient support from posterior teeth. It's important to assess the patient's occupation, medical and dental history, and lifestyle for potential risk factors [17]. It is crucial that any restorative procedure is performed only after a thorough diagnosis of the underlying causes, stabilization of the oral environment, and prevention of additional tooth damage. This approach should also focus on enhancing adhesive bonding and, when feasible, promoting the remineralization of the remaining tooth structure [90].

4.2. Occlusal management (Splint therapy)

Managing occlusion is crucial to prevent excessive wear. In case of nocturnal bruxism, hard acrylic occlusal splints are indicated. Effective occlusal adjustment can facilitate a more uniform distribution of forces throughout the tooth or restoration [39].

4.3. Material selection

The choice of restorative material should be based on both functional and aesthetic requirements, as well as the wear properties of the material. Materials with higher wear resistance should be considered for treatment of high-stress areas, such as the posterior region, while aesthetic considerations may guide the use of composites and ceramics in anterior regions.

The use of composite resin offers a clinical benefit by facilitating the patient's adaptation to occlusal changes, while also permitting the clinician to implement necessary adjustments. After the prescription is validated, the composite resin restoration can be easily substituted with another restorative material that offers enhanced long-term durability [39].

4.4. Surface Finish and Polishing

A smooth, well-polished surface reduces the potential of wear. Restorative materials should be polished after placement, and patients should be educated about maintaining the smooth surface by avoiding abrasive toothpaste and hard-bristled brushes [45,88].

4.5. Prevention of erosion

Patients should be advised to limit the intake of acidic foods and beverages and seek treatment for conditions such as acid reflux or bulimia, which can contribute to tooth erosion. Fluoride treatments, beverage modification/dietary counselling, habit change may also help to remineralize enamel and reduce the effects of erosion. In case of bulimia or reflux diseases, patients can apply to a medical doctor for the treatment of these diseases [91].

4.6. Regular monitoring

Regular dental check-ups and monitoring of wear patterns are essential for early intervention. Digital imaging and occlusal analysis can help detect wear and assess the condition of restorations and natural teeth. Also, a number of clinical indices can be used to monitor the progression of tooth surface loss [91]. Patient education is critical in controlling the progression of ongoing tooth wear [6].

5. FUTURE PERSPECTIVE FOR WEAR IN DENTISTRY

Over the decades, the management of tooth wear has changed significantly. Advancements in dental materials and deeper comprehension of specific occlusal principles have led to the adoption of minimally invasive approach as the preferred choice [92]. In the last fifty years, dentistry has witnessed numerous important advancements. These developments have led to enhanced knowledge and comprehension of dental adhesion, dental materials, and principles of clinical occlusion [93]. Developments in the application of digital technology in the clinical setting have also taken place. Each of these factors has had an impact on the management of tooth wear.

Although the criteria for restorative intervention have been defined, encompassing aesthetic, functional, and symptom-related issues, emerging data highlight the significance of tooth wear's effect on a patient's quality of life [92,93,94]. The future of wear in dentistry is evolving rapidly, driven by advances in materials science, digital technologies, and a better understanding of biomaterials and their interactions with the oral environment. With advanced materials, digital technologies, and a deeper understanding of the dynamics of wear, the industry has been poised to offer more durable, aesthetic, and sustainable dental restorations. This evolution will significantly affect how dentists approach preventive care, diagnosis, and treatment planning for wear-related issues in the oral cavity.

The following perspectives can be given regarding wear behavior in dentistry, from today to the future:

5.1. New trends in restorative biomaterials

As dental materials evolve, there's a strong focus on improving wear resistance for materials like composites, ceramics, and resin-based substances. New materials are being developed that can better withstand the mechanical forces in the mouth (biting, grinding) and maintain their structural integrity longer [95]. The use of nanomaterials in dentistry is expanding. Nano-reinforced composites and ceramics can offer higher wear resistance, better aesthetics, and superior mechanical properties [96]. Researchers are also investigating "smart" materials that can change their properties in response to environmental factors (like changes in temperature or pressure), potentially enhancing their longevity and functionality in restorative treatment [97].

The implementation of restorative care for patients experiencing tooth wear can be enhanced through the use of CAD/CAM technology. The development of advanced dental materials that exhibit improved mechanical and adhesive characteristics may enable treatment with minimal intervention. This advancement could also allow a greater number of patients to receive necessary care in a reliable manner within a primary care environment. An example is the recent introduction of polymerinfiltrated ceramic network materials (PICN) – hybrid ceramics, combining the desirable mechanical, physical and aesthetic properties of both ceramics and composites. PICN materials may be used to restore worn teeth using CAD/ CAM and without the need for tooth preparation [92].

5.2. Digital dentistry

Digital dentistry refers to a wide range of dental technologies that utilize computer-based elements, including both hardware and software. Its primary aim is to assist dental practitioners in providing treatments through computer-aided tools. The use of computer-aided design and computer-aided manufacturing (CAD/CAM) for dental impressions is gaining attention within the field. The CAD/CAM workflow encompasses various stages, including intraoral scanning, the development of a digital dental design, the milling or printing of the design, and its subsequent application in the patient's mouth [98]. Digital scanning and design technologies are also contributing to improved outcomes [5].

5.3. Minimally invasive procedures

Dentistry is shifting toward more preventive care rather than invasive treatments. Early detection of tooth wear through advanced imaging or diagnostic tools will lead to more conservative interventions, which could help to preserve natural tooth structure. Protective coatings and sealants are becoming more effective at preventing or reducing wear on teeth and dental restorations [99,100]. These materials could be applied in a way that minimizes damage from abrasion or acidic foods and drinks.

5.4. Wear impact on restorative materials

With better understanding of the effects of wear on restorative materials over time, treatments will become more durable. There may be new ways to predict how a material will wear over the long term and design restorations that better mimic natural tooth behavior. The increasing awareness of bruxism, or teeth grinding, as a prevalent concern has led to a rise in the popularity of wear-resistant materials and treatments aimed at mitigating this problem. Night guards, splints, and more resilient dental restorations are tailored for this growing problem.

5.5. Personalized dentistry

Tailored strategies may exist for addressing dental wear, taking into account genetic and lifestyle factors when selecting dental materials. For example, individuals who are more prone to bruxism or wear due to certain health conditions may receive tailored solutions to reduce the risk of damage. With the advancements in digital impressions, restorations can be designed more precisely, reducing stress on individual teeth, thus limiting excessive wear.

5.6. Sustainability and environmental concerns

As the emphasis on sustainability grows worldwide, it is probable that future dental materials will be developed with environmental factors taken into account. This could mean more biodegradable or recyclable dental products, along with more energy-efficient manufacturing methods. The focus on durable, long-lasting materials will also reduce the need for frequent replacements, which is not only better for patients but also for the environment by reducing waste.

5.7. Wear monitoring technology

Future developments might include wearable devices or smart sensors that can be integrated into dental restorations or orthodontic appliances. These sensors could provide real-time data on how much wear is occurring, enabling quicker adjustments and preventative actions.

5.8. Better patient education

As technology improves, dental professionals will have more interactive tools to educate patients on the wear of their teeth, its causes, and prevention strategies. Patients will be able to monitor their oral habits, such as grinding or clenching, with wearable devices and apps, allowing for more proactive care.

5.9. Nanotechnology

Nanotechnology is creating significant advancements in various fields, including medicine, dentistry, and manufacturing. In few years, the basic science of nanotechnology has changed the dental practice. By utilizing nanoscale materials and technologies, nanotechnology enables advancements in aesthetics, durability, and functionality of dental restorations [101]. The development of nanomaterials, especially in dentistry, presents advantages such as superior aesthetics, but still requires improvement in mechanical properties compared to existing materials.

6. CONCLUSIONS

Wear in restorative dentistry still remains a complex and multifactorial phenomenon that critically affects both natural teeth and restorative bio-materials. The interplay of mechanical, chemical, and biological processes—such as attrition, abrasion, erosion, abfraction, fatigue, and adhesive wear—requires a nuanced understanding of material science, oral biomechanics, and patient-specific factors. These mechanisms often act synergistically, leading to progressive deterioration of both natural dental tissues and restorative materials. An ideal restorative bio-material should exhibit sufficient wear resistance while minimizing damage to the opposing dentition and preserving oral function and aesthetics.

Advancements in wear simulation technologies and characterization methods have provided valuable insights into material performance under both in-vitro and in-vivo conditions. Numerous testing techniques, including simulated mastication, tribological assessments, and advanced characterization tools like SEM, AFM, and profilometry, have been developed to evaluate wear behavior accurately. These methods offer essential insights into material performance and facilitate the optimization of clinical outcomes. However, limitations still exist in replicating the full complexity of the oral environment. Therefore, a combination of laboratory testing and long-term clinical studies is essential to validate the wear resistance of current and future dental materials. Clinical strategies such as risk assessment, occlusal management, appropriate material selection, and regular monitoring play vital roles in minimizing wear and extending the longevity of restorations.
Future perspectives focus on personalized, minimally invasive restorative approaches, enhanced by the integration of digital technologies and predictive wear models. As dentistry progresses, further research into wear mechanisms and continued innovation in restorative materials will be essential to improve long-term clinical success and patient quality of life.

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7. REFERENCES

[1] A. Ramalho and J. C. Miranda, "The relationship between wear and dissipated energy in sliding systems," Wear, vol. 260, no. 4–5, pp. 361–367, 2006, doi: 10.1016/j.wear.2005.02.121.
[2] R. Wang, Y. Zhu, C. Chen, Y. Han, and H. Zhou, "Tooth wear and tribological investigations in dentistry," Appl. Bionics Biomech., vol. 2022, Article ID 2861197, Jun. 9, 2022, doi: 10.1155/2022/2861197.
[3] B. Loomans, N. Opdam, T. Attin, D. Bartlett, D. Edelhoff, R. Frankenberger, G. Benic, S. Ramseyer, P. Wetselaar, B. Sterenborg, R. Hickel, U. Pallesen, S. Mehta, S. Banerji, A. Lussi, and N. Wilson, "Severe tooth wear: European consensus statement on management guidelines," J. Adhes. Dent., vol. 19, no. 2, pp. 111–119, 2017, doi: 10.3290/j.jad.a38102.
[4] D. Bartlett and S. O'Toole, "Tooth wear and aging," Aust. Dent. J., vol. 64, Suppl. 1, pp. S59–S62, Jun. 2019, doi: 10.1111/adj.12681.
[5] S. D. Heintze, F.-X. Reichl, and R. Hickel, "Wear of dental materials: Clinical significance and laboratory wear simulation methods - A review," Dent. Mater. J., vol. 38, no. 3, pp. 343–353, Jun. 2019, doi: 10.4012/dmj.2018-140
[6] Tooth Wear, Int. Dent. J., vol. 74, no. 1, pp. 163–164, 2024, ISSN 0020-6539.
[7] L. H. Mair, "Wear in dentistry - Current terminology," J. Dent., vol. 20, pp. 140–144, 1992.

[8] Y. Morozova, P. Holik, R. Ctvrtlik, J. Tomastik, L. Foltasova, and A. Harcekova, "Tooth wear—Fundamental mechanisms and diagnosis," IOSR J. Dent. Med. Sci., vol. 15, pp. 84–91, 2016, doi: 10.9790/0853-1505088491

[9] A. Lanza, A. Ruggiero, and L. Sbordone, "Tribology and dentistry: a commentary," Lubricants, vol. 7, no. 6, 2019, doi: 10.3390/lubricants7060052.

[10] Y.-Q. Wu, J. A. Arsecularatne, and M. Hoffman, "Attrition-corrosion of human dental enamel: a review," Biosurface Biotribol., vol. 3, no. 4, pp. 196–210, 2017, doi: 10.1016/j.bsbt.2017.12.001.

[11] A. Lee, L. H. He, K. Lyons, and M. V. Swain, "Tooth wear and wear investigations in dentistry," J. Oral Rehabil., vol. 39, no. 3, pp. 217–225, Mar. 2012, doi: 10.1111/j.1365-2842.2011.02257.x.

[12] J. Rees and S. Somi, "A guide to the clinical management of attrition," Br. Dent. J., vol. 224, pp. 319–323, 2018, doi: 10.1038/sj.bdj.2018.169.

[13] A. Warreth, E. Abuhijleh, M. A. Almaghribi, G. Mahwal, and A. Ashawish, "Tooth surface loss: A review of literature," Saudi Dent. J., vol. 32, no. 2, pp. 53–60, Feb. 2020, doi: 10.1016/j.sdentj.2019.09.004.

[14] A. Milose, "Abrasion: A common dental problem revisited," Prim. Dent. J., vol. 6, no. 1, pp. 32–36, 2017.

[15] E. d'INCAU and P. SAULUE, "Understanding dental wear," J. Dentofacial Anomalies Orthod., vol. 15, no. 1, pp. 1–19, 2012.

[16] C. Ganss, "Definition of erosion and links to tooth wear," in Dental Erosion, A. Lussi, Ed., Monogr. Oral Sci., vol. 20, Basel, Switzerland: Karger, 2006, pp. 9–16.

[17] J. A. Kaidonis, "Oral diagnosis and treatment planning: part 4. Non-carious tooth surface loss and assessment of risk," Br. Dent. J., vol. 213, no. 4, pp. 155–161, Aug. 2012, doi: 10.1038/sj.bdj.2012.7

[18] T. Donovan, C. Nguyen-Ngoc, I. Abd Alraheam, and K. Irusa, "Contemporary diagnosis and management of dental erosion," J. Esthet. Restor. Dent., vol. 33, no. 1, pp. 78–87, Jan. 2021, doi: 10.1111/jerd.12706.

[19] N. Eliaz, "Corrosion of metallic biomaterials: A review," Materials (Basel), vol. 12, no. 3, p. 407, Jan. 28, 2019, doi: 10.3390/ma12030407.

[20] Bartlett, D.W.; Shah, P, "A Critical Review of Non-carious Cervical (Wear) Lesions and the Role of Abfraction, Erosion, and Abrasion". Journal of Dental Research. 85 (4) (2006) 306–312.

[21] G. S. Sarode and S. C. Sarode, "Abfraction: A review," J. Oral Maxillofac. Pathol., vol. 17, no. 2, pp. 222–227, May 2013, doi: 10.4103/0973-029X.119788

[22] A. N. Badavannavar, S. Ajari, K. U. S. Nayak, and S. Khijmatgar, "Abfraction: Etiopathogenesis, clinical aspect, and diagnostic-treatment modalities: A review," Indian J. Dent. Res., vol. 31, no. 2, pp. 305–311, Mar.-Apr. 2020, doi: 10.4103/ijdr.IJDR_863_18.

[23] J. O. Grippo, "Abfractions: A new classification of hard tissue lesions of teeth," J. Esthet. Dent., vol. 3, no. 1, pp. 14–19, Jan.-Feb. 1991, doi: 10.1111/j.1708-8240.1991.tb00799.x.

[24] J. O. Grippo, M. Simring, and S. Schreiner, "Attrition, abrasion, corrosion, and abfraction revisited: A new perspective on tooth surface lesions," J. Am. Dent. Assoc., vol. 135, no. 8, pp. 1109–1118, Aug. 2004, doi: 10.14219/jada.archive.2004.0369, Erratum in: J. Am. Dent. Assoc., vol. 135, no. 10, p. 1376, Oct. 2004, PMID: 15387049.

[25] J. S. Rees, "A review of the biomechanics of abfraction," Eur. J. Prosthodont. Restor. Dent., vol. 8, no. 4, pp. 139–144, Dec. 2000.

[26] B. Hur, H. C. Kim, J. K. Park, and A. Versluis, "Characteristics of non-carious cervical lesions—an ex vivo study using micro computed tomography," J. Oral Rehabil., vol. 38, no. 6, pp. 469–474, Jun. 2011, doi: 10.1111/j.1365-2842.2010.02172.x.

[27] R. W. Wassell, J. F. McCabe, and A. W. Walls, "A two-body frictional wear test," J. Dent. Res., vol. 73, no. 9, pp. 1546–1553, Sep. 1994, doi: 10.1177/00220345940730091001.

[28] C. H. Hacker, W. C. Wagner, and M. E. Razzoog, "An in vitro investigation of the wear of enamel on porcelain and gold in saliva," J. Prosthet. Dent., vol. 75, no. 1, pp. 14–17, Jan. 1996, doi: 10.1016/s0022-3913(96)90412-6.

[29] K. J. Söderholm and N. D. Richards, "Wear resistance of composites: a solved problem?," Gen. Dent., vol. 46, no. 3, pp. 256–263, 1998.

[30] J. F. Bates and A. G. Knapton, "Metals and alloys in dentistry," Int. Metals Rev., vol. 22, no. 1, pp. 39–60, 1977, doi: 10.1179/imtr.1977.22.1.39.

[31] W. S. Oh, R. Delong, and K. J. Anusavice, "Factors affecting enamel and ceramic wear: a literature review," J. Prosthet. Dent., vol. 87, no. 4, pp. 451–459, Apr. 2002, doi: 10.1067/mpr.2002.123851.

[32] K. Chun, H. Choi, and J. Lee, "Comparison of mechanical property and role between enamel and dentin in the human teeth," J. Dent. Biomech., vol. 5, p. 1758736014520809, 2014, doi: 10.1177/1758736014520809.
[33] J. Tokunaga, H. Ikeda, Y. Nagamatsu, S. Awano, and H. Shimizu, "Wear of polymer-infiltrated ceramic network materials against enamel," Materials, vol. 15, no. 7, p. 2435, 2022, doi: 10.3390/ma15072435.
[34] A. Hatanaka, T. Sawada, K. Sen, T. Saito, K. Sasaki, T. Someya, M. Hattori, and S. Takemoto, "Wear behavior between aesthetic restorative materials and bovine tooth enamel," Materials (Basel), vol. 15, no. 15, p. 5234, Jul. 2022, doi: 10.3390/ma15155234.
[35] M. León Velastegui, J. M. Montiel-Company, R. Agustín-Panadero, C. Fons-Badal, and M. F. Solá-Ruíz, "Enamel wear of antagonist tooth caused by dental ceramics: Systematic review and meta-analysis," J. Clin. Med., vol. 11, no. 21, p. 6547, Nov. 2022, doi: 10.3390/jcm11216547.
[36] A. J. de Gee, P. Pallav, and C. L. Davidson, "Effect of abrasion medium on wear of stress-bearing composites and amalgam in vitro," J. Dent. Res., vol. 65, pp. 654–658, 1986.
[37] J. J. Kruzic, J. A. Arsecularatne, C. B. Tanaka, M. J. Hoffman, and P. F. Cesar, "Recent advances in understanding the fatigue and wear behavior of dental composites and ceramics," J. Mech. Behav. Biomed. Mater., vol. 88, pp. 504-533, Dec. 2018, doi: 10.1016/j.jmbbm.2018.08.008.
[38] K. Hemmings, U. Darbar, and S. Vaughn, "Tooth wear treated with direct composite at an increased vertical dimension: Results at 30 months," J. Prosthet. Dent., vol. 83, pp. 287–293, 2000.
[39] S. B. Mehta, S. Banerji, B. J. Millar, and J. M. Suarez-Feito, "Current concepts on the management of tooth wear: Part 2. Active restorative care 1: The management of localised tooth wear," Br. Dent. J., vol. 212, no. 2, pp. 73-82, Jan. 27, 2012, doi: 10.1038/sj.bdj.2012.48.
[40] Y. Morozova, P. Holik, R. Ctvrtlik, J. Tomastik, B. Azar, E. Sedlata Juraskova, A. Harcekova, "Methods of wear measuring in dentistry," IOSR J. Dent. Med. Sci., vol. 16, no. 6, pp. 63–68, 2016, doi: 10.9790/0853-1506116368.
[41] E. C. Yilmaz and R. Sadeler, "Investigation of two- and three-body wear resistance on flowable bulkfill and resin-based composites," Mech. Compos. Mater., vol. 54, no. 3, pp. 395 - 402, 2018, doi: 395–402, 2018. doi: 10.1007/s11029-018-9750-8
[42] L. Alecrim, J. Ferreira, M. D. Salvador, A. Borrell, and E. Pallone, "Wear behavior of conventional and spark plasma sintered Al2O3-NbC nanocomposites," Int. J. Appl. Ceram. Technol., vol. 15, no. 2, pp. 418–425, 2018.
[43] M. A. Osiewicz, A. Werner, J. Pytko-Polonczyk, F. J. M. Roeters, and C. J. Kleverlaan, "Contact- and contact-free wear between various resin composites," Dent. Mater., vol. 31, no. 2, pp. 134–140, 2015, doi: 10.1016/j.dental.2014.11.007
[44] E. C. Yilmaz and R. Sadeler, "Investigation of three-body wear of dental materials under different chewing cycles," Sci. Eng. Comp. Mater., vol. 25, no. 4, pp. doi: 781–787, 2018, doi: 10.1515/secm-2016-0385
[45] K. Dulger and G. Purcek, "Friction and wear characteristics of ceramic filler containing dental restorative composites in different test media," J. Aust. Ceram. Soc., vol. 2025, p. 11, 2025, doi: 10.1007/s41779-025-01155-6.
[46] A. V. Stück, S. Raith, and S. Reich, "Twenty-four months in vivo wear of enamel antagonists to lithium disilicate implant crowns - A pilot study," J. Dent., vol. 124, p. 104215, Sep. 2022, doi: 10.1016/j.jdent.2022.104215.
[47] M. K. Al-Omiri, R. Harb, O. A. Hammad, P. J. Lamey, E. Lynch, T. J. Clifford, "Quantification of tooth wear: Conventional vs new method using toolmakers microscope and a three-dimensional measuring technique," J. Dent., vol. 38, no. 7, pp. 560–568, 2010, doi: 10.1016/j.jdent.2010.03.016.
[48] D. Bartlett and C. Dugmore, "Pathological or physiological erosion - Is there a relationship to age?" Clin. Oral Invest., vol. 12, no. SUPPL. 1, pp. 27–31, 2008, doi: 10.1007/s00784-007-0177-1.
[49] F. J. Lopez-Frías, L. Castellanos-Cosano, J. Martan-Gonzalez, J. M. Llamas-Carreras, and J. J. Segura-Egea, "Clinical measurement of tooth wear: Tooth wear indices," J. Clin. Exp. Dent., vol. 4, no. 1, pp. 48–53, 2012, doi: 10.4317/jced.50592.
[50] N. Urcelay Moreno, S. F. Bertuol Gessi, M. M'Rabat Benabdallah, I. J. Thuissard, and A. Santamaria-Laorden, "In vivo prospective randomised study of the wear of dental restorations using an intraoral scanner and its correlation with visual assessment," J. Dent., vol. 153, p. 105471, Feb. 2025, doi: 10.1016/j.jdent.2024.105471.

[51] E. Maier, J. Ruben, W. M. Palin, E. Bronkhorst, M. Olmos, R.E. Matta & B. Loomans., "Developing an optimised method for accurate wear testing of dental materials using the 'Rub&Roll' device," Sci. Rep., vol. 14, p. 17885, 2024, doi: 10.1038/s41598-024-68873-y.
[52] M. C. R. B. Petersa, R. Delong, M. R. Pintado, U. Pallesen, V. Qvist, and W. H. Douglas, "Comparison of two measurement techniques for clinical wear," J. Dent., vol. 27, pp. 479–485, 1999.
[53] C. Wulfman, V. Koenig, and A. K. Mainjot, "Wear measurement of dental tissues and materials in clinical studies: A systematic review," Dent. Mater., vol. 34, no. 6, pp. 825-850, 2018, doi: 10.1016/j.dental.2018.03.002.
[54] S. D. Heintze, A. Cavalleri, M. Forjanic, G. Zellweger, and V. Rousson, "A comparison of three different methods for the quantification of the in vitro wear of dental materials," Dent. Mater., vol. 22, pp. 1051–1062, 2006.
[55] P. Lambrechts, E. Debels, K. Van Landuyt, M. Peumans, and B. Van Meerbeek, "How to simulate wear? Overview of existing methods," Dent. Mater., vol. 22, no. 8, pp. 693–701, Aug. 2006, doi: 10.1016/j.dental.2006.02.004.
[56] S. D. Heintze, "How to qualify and validate wear simulation devices and methods," Dent. Mater., vol. 22, pp. 712–734, 2006.
[57] N. Bayar, M. Nezir, and S. Özcan, "Review in vitro testing methods for the evaluation of the mechanical properties of composite resins," Cilt: 13, Sayı: 3, pp. 550-561, 2024, doi: 10.54617/adoklinikbilimler.1435652
[58] "Kavo Jaw Simulators," Kavo. [Online]. Available: https://www.kavo.com/en/products/dental-education/patient-simulators/jaw-simulators.
[59] M. Steiner, M. E. Mitsias, K. Ludwig, and M. Kern, "In vitro evaluation of a mechanical testing chewing simulator," Dent. Mater., vol. 25, pp. 494–499, 2009.
[60] "Mawad Lab Chewing Simulator," [Online]. Available: https://mawadlab.com/case/chewing-simulator.
[61] E. Ç. Yilmaz and R. Sadeler, "A literature review on chewing simulation and wear mechanisms of dental biomaterials," J. Bio- and Tribo-Corrosion, vol. 7, p. 91, 2021, doi: 10.1007/s40735-021-00529-0
[62] E. C. Yilmaz and R. Sadeler, "Effects of contact-stress on wear behavior of zirconia-reinforced lithium silicate glass-ceramic," Biomed. Biotechnol. Res. J., vol. 4, no. 1, pp. 51–54, 2020.
[63] S. Rues, G. Huber, P. Rammelsberg, and T. Stober, "Effect of impact velocity and specimen stiffness on contact forces in a weight-controlled chewing simulator," Dent. Mater., vol. 27, pp. 1267–1272, 2011.
[64] A. J. de Gee and P. Pallav, "Occlusal wear simulation with the ACTA wear machine," J. Dent., vol. 22, pp. S21–S27, 1994.
[65] A. R. Benetti, L. Larsen, A. H. Dowling, and G. J. P. Fleming, "Assessment of wear facets produced by the ACTA wear machine," J. Dent., vol. 45, pp. 19–25, 2016, doi: 10.1016/j.jdent.2015.12.003
[66] J. Enax, F. Meyer, E. Schulze zur Wiesche, I. C. Fuhrmann, and H.-O. Fabritius, "Toothpaste abrasion and abrasive particle content: Correlating high-resolution profilometric analysis with relative dentin abrasivity (RDA)," Dent. J., vol. 11, no. 79, 2023, doi: 10.3390/dj11030079
[67] U. Pertiwi, Y. K. Eriwati, and B. Irawan, "Surface changes of enamel after brushing with charcoal toothpaste," J. Phys.: Conf. Ser., vol. 12002, 2017.
[68] S. D. Palandi, M. Kury, M. Z. D. Picolo, C. S. S. Coelho, and V. Cavalli, "Effects of activated charcoal powder combined with toothpastes on enamel color change and surface properties," J. Esthet. Restor. Dent., vol. 32, pp. 783–790, 2020, doi: 10.1111/jerd.12646
[69] R. G. Ledder, J. Latimer, S. Forbes, J. L. Penney, P. K. Sreenivasan, and A. J. McBain, "Visualization and quantification of the oral hygiene effects of brushing, dentifrice use, and brush wear using a tooth brushing simulator," Front. Public Health, vol. 7, 2019, doi: 10.3389/fpubh.2019.00091
[70] M. Eisenburger, R. P. Shellis, and M. Addy, "Comparative study of wear of enamel induced by alternating and simultaneous combinations of abrasion and erosion in vitro," Caries Res., vol. 37, no. 6, pp. 450–455, 2003.
[71] J. S. Almeida e Silva, E. Medeiro de Araujo Jr., E. Araujo, "Cigarette smoke affects bonding to dentin," Gen. Dent., vol. 58, no. 4, pp. 326–330, 2010.
[72] A. Greuling, J. M. Emke, and M. Eisenburger, "Abrasion behaviour of different charcoal toothpastes when using electric toothbrushes," Dent. J., vol. 9, no. 97, 2021, doi: 10.3390/dj9080097

[73] M. Baig, R. B. Cook, J. Pratten, and R. Wood, "Evolution of wear on enamel caused by tooth brushing with abrasive toothpaste slurries," Wear, vol. 476, p. 203580, 2021, doi: 10.1016/j.wear.2020.203580.

[74] B. Hamza, L. Martinola, P. Körner, A. Gubler, T. Attin, and F. J. Wegehaupt, "Effect of brushing force on the abrasive dentin wear using slurries with different abrasivity values," Int. J. Dent. Hygiene, vol. 21, pp. 172–177, 2023, doi: 10.1111/idh.12620

[75] V. Torno and P. Soares, "Tribological behavior and wear mechanisms of dental resin composites with different polymeric matrices," J. Mech. Behav. Biomed. Mater., vol. 144, p. 105962, Aug. 2023, doi: 10.1016/j.jmbbm.2023.105962.

[76] A. Morshed, H. Wu, and Z. Jiang, "A Comprehensive Review of Water-Based Nanolubricants," Lubricants, vol. 9, no. 9, p. 89, 2021, doi: 10.3390/lubricants9090089

[77] Z. Qiu, C. Liu, H. Wang, X. Yang, F. Fang, and J. Tang, "Crack propagation and the material removal mechanism of glass-ceramics by the scratch test," J. Mech. Behav. Biomed. Mater., vol. 64, pp. 75-85, Dec. 2016, doi: 10.1016/j.jmbbm.2016.07.021.

[78] E. G. Mota and K. Subramani, Emerging Nanotechnologies in Dentistry, 2nd ed., Elsevier Inc., 2018, pp. 59-82. ISBN: 978-0-12-812291-4.

[79] T. Attin, U. Koidl, W. Buchalla, H. G. Schaller, A. M. Kielbassa, and E. Hellwig, "Correlation of microhardness and wear in differently eroded bovine dental enamel," Arch. Oral Biol., vol. 42, no. 3, pp. 243–250, 1997.

[80] K. Dülger, "The Effect of Additional Finishing and Polishing Sequences on Hardness and Roughness of Two Different Dental Composites: An In Vitro Study," J. Adv. Oral Res., vol. 13, no. 2, pp. 216-224, 2022, doi: 10.1177/23202068221121518.

[81] A. Kakaboura, M. Fragouli, C. Rahiotis, and N. Silikas, "Evaluation of surface characteristics of dental composites using profilometry, scanning electron, atomic force microscopy and gloss-meter," J. Mater. Sci. Mater. Med., vol. 18, pp. 155-163, 2007, doi: 10.1007/s10856-006-0675-8.

[82] L. Levrini, G. Di Benedetto, and M. Raspanti, "Dental wear: A scanning electron microscope study," Biomed. Res. Int., vol. 2014, p. 340425, 2014, doi: 10.1155/2014/340425.

[83] A. Barhoum, J. Jeevanandam, and M. K. Danquah, Fundamentals of Bionanomaterials, vol. 6, T. R. Shojaei, S. Soltani, and M. Derakhshani, Eds., 2022, pp. 139-174.

[84] G. R. Goldstein, B. R. Barnhard, and B. Penugonda, "Profilometer, SEM, and visual assessment of porcelain polishing methods," J. Prosthet. Dent., vol. 65, pp. 627-634, 1991, doi: 10.1016/0022-3913(91)90196-4.

[85] N. Gadegaard, "Atomic force microscopy in biology: technology and techniques," Biotech. Histochem., vol. 81, pp. 87–97, 2006, doi: 10.1080/10520290600783143.

[86] A. P. Elfick, S. M. Green, I. M. Pinder, and A. Unsworth, "A novel technique for the detailed size characterization of wear debris," J. Mater. Sci. Mater. Med., vol. 11, no. 5, pp. 267–271, 2000.

[87] J. A. Savio III, L. M. Overcamp, and J. Black, "Size and shape of biomaterial wear debris," Clin. Mater., vol. 15, no. 2, pp. 101–147, 1994, doi: 10.1016/0267-6605(94)90076-0

[88] K. Dülger and G. Purcek, "Effect of contemporary polishing systems on hardness and roughness of one-shaded dental composites," J. Aust. Ceram. Soc., vol. 2024, pp. 1-10, doi: 10.1007/s41779-024-01100-z.

[89] N. D. Yanıkoglu and R. E. Sakarya, "Test methods used in the evaluation of the structure features of the restorative materials: a literature review," J. Adv. Dent. Res., vol. 22, no. 3, pp. 345–350, 2024, doi: 10.1016/j.jmrt.2020.06.049

[90] I. A. Meyers, "Minimum intervention dentistry and the management of tooth wear in general practice," Aust. Dent. J., vol. 58, Suppl. 1, pp. 60-65, Jun. 2013, doi: 10.1111/adj.12050.

[91] S. B. Mehta, S. Banerji, B. J. Millar, and J. M. Suarez-Feito, "Current concepts on the management of tooth wear: part 1. Assessment, treatment planning and strategies for the prevention and the passive management of tooth wear," Br. Dent. J., vol. 212, no. 1, pp. 17-27, Jan. 2012, doi: 10.1038/sj.bdj.2011.1099.

[92] S. B. Mehta and S. Banerji, "The Management of Tooth Wear: Past, Present and Future," Conservative Dentistry, vol. 50, pp. 375-382, 2023, doi: 10.12968/denu.2023.50.5.375

[93] S. B. Mehta, B. A. C. Loomans, S. Banerji, E M Bronkhorst , D Bartlett , "An investigation into the impact of tooth wear on the oral health-related quality of life among adult dental patients in the United Kingdom, Malta, and

Australia," J. Dent., vol. 99, p. 103409, 2020, doi: 10.1016/j.jdent.2020.103409.
[94] M. H. M. Li and E. Bernabé, "Tooth wear and quality of life among adults in the United Kingdom," J. Dent., vol. 55, pp. 48–53, 2016, doi: 10.1016/j.jdent.2016.09.013
[95] S. Iftikhar, N. Jahanzeb, M. Saleem, S. U. Rehman, J. P. Matinlinna, and A. S. Khan, "The trends of dental biomaterials research and future directions: A mapping review," Saudi Dent. J., vol. 33, no. 5, pp. 229-238, 2021, doi: 10.1016/j.sdentj.2021.01.002.
[96] V. Bonilla-Represa, C. Abalos-Labruzzi, M. Herrera-Martinez, and M. O. Guerrero-Pérez, "Nanomaterials in Dentistry: State of the Art and Future Challenges," Nanomaterials, vol. 10, no. 9, p. 1770, Sep. 2020, doi: 10.3390/nano10091770.
[97] L. M. Maloo, A. Patel, S. H. Toshniwal, and A. D. Bagde, "Smart materials leading to restorative dentistry: An overview," Cureus, vol. 14, no. 10, p. e30789, Oct. 2022, doi: 10.7759/cureus.30789.
[98] "Introduction to Digital Dentistry," 3Shape, [Online]. Available: https://www.3shape.com/en/blog/digital-dentistry/intro-digital-dentistry.
[99] O. C. Aktas, K. Puchert, E. E. Vurucu, B. Ersöz, S. Veziroglu, and S. Sen, "A review on nanocomposite coatings in dentistry," J. Mater. Sci., vol. 59, pp. 17991–18008, 2024, doi: 10.1007/s10853-024-09915-8
[100] L. C. Ardelean and L. C. Rusu, "Advanced Biomaterials, Coatings, and Techniques: Applications in Medicine and Dentistry," Coatings, vol. 12, no. 6, p. 797, 2022, doi: 10.3390/coatings12060797
[101] N. Chaudhary, V. Chaudhary, M. Bansal, M. Karol, G. Singh, S. Kumawat, S. Sharma, and H. Jain, "Nanotechnology in restorative dentistry: A review," Int. J. Appl. Dent. Sci., vol. 10, no. 4, pp. 192-195, 2024, doi: 10.22271/oral.2024.v10.i4c.2063