

# A Comprehensive Review of Wear in Restorative Dentistry: From Enamel to Advanced Restorative Materials

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## Keywords:

*Wear in dentistry*  
*Wear mechanisms*  
*Dentistry*  
*Dental restorative materials*  
*Dental wear test techniques*

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Received: 29 June 2025

Revised: 5 July 2025

Accepted: 10 August 2025



## ABSTRACT

*Wear is a significant concern for dental tissues as well as for dental materials that must have sufficient wear resistance without causing harm to 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 each other. Various materials and techniques for rehabilitating worn teeth have been discussed in the literature. Some data are also available on the clinical performance of restorations used for the treatment of tooth wear. Therefore, this study presents a comprehensive review of wear phenomena in 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. This review explores the clinical significance of tooth wear, material-specific wear behavior, and testing methodologies, such as in vivo observations and in vitro simulations, including chewing simulators, tribological tests, and advanced surface analysis techniques. This study also discusses preventive strategies, clinical decision-making, and future directions in restorative dentistry, highlighting innovations in biomaterials, digital technologies, and personalized treatment approaches aimed at minimizing wear and enhancing patient outcomes.*

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## 1. INTRODUCTION

Wear in dentistry is a critical phenomenon that affects the longevity and function of restorative materials and 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 human habits [1]. Wear occurs when dental materials or natural

tooth surfaces undergo abrasion, attrition, or erosion due to 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 the dental care. Many studies have been published on the wear of dental materials and natural teeth. In addition, review and overview papers have been published to clarify 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 to address these gaps. This review emphasizes the clinical importance of wear, specifically concerning natural teeth and restorative materials, as well as the laboratory techniques used to replicate wear on these restorative materials.

## 2. WEAR MECHANISMS IN TEETH AND RESTORATIVE MATERIALS

Dental enamel exhibits significant resistance to wear, with an average annual vertical loss of approximately 20–30  $\mu\text{m}$  in 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 it diminishes. Enamel wear primarily occurs due to microfracturing and is marked by delamination and microploving, whereas dentin wear is characterized by the formation of ductile chips [5].

In dentistry, tooth wear refers 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]. Wear may stem from various mechanisms, such as erosion, attrition, abrasion, and possibly dental abfraction, which can occur independently or in conjunction with one another. These mechanisms may be triggered by exposure to acids of nonbacterial origin and 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 structures over time due to mechanical, chemical, or biological factors [8]. Understanding these mechanisms is important

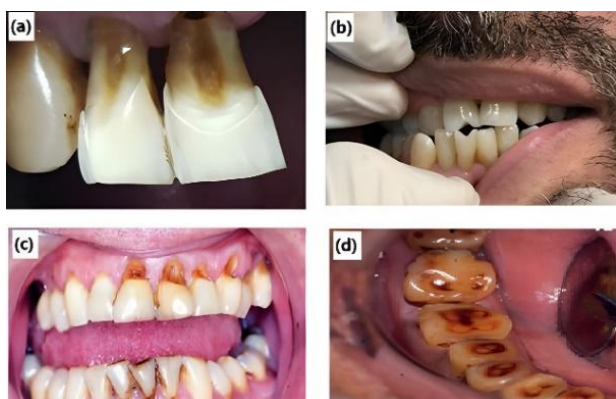
because they affect the longevity and functionality of dental restorations and natural teeth [2]. There are several types of wear mechanisms in natural teeth and dental materials, as outlined below. Each of these mechanisms contributes to the overall wear of teeth or dental materials and influences the 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 due to direct contact with opposing surfaces during mastication [6,10]. It mainly occurs when natural teeth grind against each other or 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 teeth results in wear patterns on opposing teeth. In the early stages, there may be small, shiny areas on the cusp tips or slight flattening of the incisal edges, whereas severe attrition can expose the dentin, potentially accelerating the wear process [11]. Other clinical signs include 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, headache in the temporal area, and grinding or clenching of teeth while awake [12]. Fig. 1(a)–(b) show tooth attrition because of tooth-to-tooth contact, which caused decreased vertical dimensions and esthetics. Fig. 1(c) shows the effect of attrition caused by the ceramic prosthesis on the opposite teeth. Fig. 1(d) shows the occlusal and incisal surfaces of teeth worn by attrition.



**Fig. 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 of the opposite natural teeth. (d) A 66-year-old female patient with dental attrition on the occlusal surfaces of the mandible.

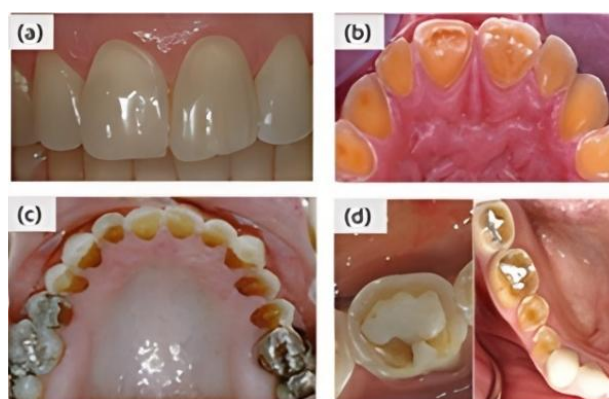
**Abrasion:** Abrasive wear refers to the loss of material from a surface owing to the mechanical action of harder materials scraping against softer surfaces. In dentistry, abrasion is commonly caused by external factors such as abrasive toothpaste, hard bristles, and vigorous brushing techniques. It may also be due to 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, such as the posterior teeth [13]. Other factors may include chewing nuts, pens, pica, pipe smoking, eating stone-ground bread, eating unwashed food with sand, and using teeth as tools. Some typical examples of abrasion are shown in Fig. 2(a)–(d) [13,14]. As shown in Fig 2(a), wide abrasion lesions occurred because of the use of miswak. Fig 2(b) shows the abrasive wear on the incisal surfaces due to the consumption of dried sunflower seeds. Fig 2(c) represents the abrasion lesions caused by an inappropriate brushing technique. The effect of chewing betel nuts on the occlusal surfaces of posterior teeth is shown Fig 2(d).



**Fig. 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 the teeth, showing inappropriate force and brushing technique with the right hand [14]. (d) Abrasion lesions because of chewing betel nuts [14].

**Erosion and corrosive wear:** Erosion refers to the chemical degradation of a 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) [6,15-17]. The acids, which are 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 the 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 types of erosive wear are shown in Fig. 3(a)–(d) [18]. In Fig 3(a), an example of cervical erosion lesions on the anterior teeth caused by drinking diet cola and holding it in the muco-buccal fold is presented. Fig 3(b) shows, a patient with palatal erosion lesions due to gastroesophageal reflux. Palatal erosion resembling the pattern seen in 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 are shown.

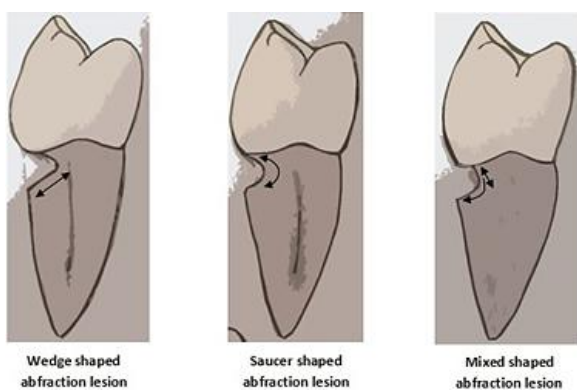


**Fig. 3.** (a) Cervical erosion lesions on the anterior teeth caused by drinking diet cola and holding it in the muco-buccal fold. (b) Patient with palatal erosion lesions due to gastroesophageal reflux. (c) Palatal erosion in a patient who drinks five glasses of champagne per night. (d) Restorations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

Corrosive wear may affect 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 due to chemical reactions with saliva or food. Corrosion can cause a material to lose its strength, functionality, and aesthetic appearance. The oral cavity is a catalyst for corrosion. It remains consistently moist and frequently experiences temperature fluctuations. The foods and beverages consumed exhibit a broad spectrum of pH levels [19].

**Abfraction:** Abfraction refers to the loss of tooth structure along the gingival margin, presenting in various clinical forms [20]. These lesions occur in

both the 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 functions, often accompanied by pathological wear, such as abrasion and erosion [22,23]. It is based on the relationship between stress concentration and occlusal loading in the cervical region of the tooth and is frequently observed 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 laterally towards the cervical area. This causes tooth cusp flexure, resulting in the collection of stress in the cervical area. These stresses cause fractures and breakdown of hydroxyapatite bonds in the enamel [24,25]. Abrasion lesions generally appear in three shapes: wedge, saucer, or mixed patterns [26]. Wedge- and saucer-shaped lesions are the most common, whereas mixed lesions are less frequently identified in the oral cavity. As shown in Fig.4, wedge-shaped lesions have the sharpest internal line angles, whereas saucer- or mixed-shaped lesions may present either a smooth internal surface or a range of variations [26].



**Fig. 4.** The forming mechanism of abfraction and its examples [20,26].

**Fatigue wear:** Fatigue wear in dentistry refers to the gradual deterioration or damage of dental materials owing 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 stress cycles. In dentistry, fatigue wear can occur when a dental restoration is subjected to 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 restoration failure

over time. Common dental materials such as composite resins, ceramics, and metals are all susceptible to some degree of fatigue wear, although different materials behave differently under stress. Fig.5. shows the typical fatigue wear of enamel in an 82 year-old male [15].



**Fig. 5.** Fatigue wear of enamel in an 82 year-old male with 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, occurs when two surfaces experience significant pressure and move against each other. 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 that of cold welding [15]. In vitro two-body friction tests have demonstrated a transfer of material to enamel (or an analog of enamel) from restorative materials such as amalgam, gold, and some composites under high pressure [27-29].

Conversely, the choice of material for dental restorations is a critical factor in managing wear. Several commonly used materials have distinct wear characteristics/mechanisms.

**Metals:** The essential importance of metallic materials, including gold, silver, copper, and alloys such as cobalt-chromium and titanium, is emphasized because of their exceptional mechanical properties in dental restorations. These properties include a high elastic modulus, tensile strength, hardness, and wear resistance [30]. Gold is highly wear-resistant 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  $492\pm 16$  Hv and  $1287\pm 33$  Hv, which is considerably greater than the hardness of bovine tooth enamel ( $303\pm 14$  Hv). Furthermore, bovine teeth are utilized as abraders and substrate specimens because of 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 [32-34]. In a study that evaluated the wear of the antagonist tooth in ceramic restorations, feldspathic produced greater wear of the antagonist tooth from ceramic restorations linearly and volumetrically [35]. In addition, zirconia generates the least wear, which decreases over time and is 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 for anterior and posterior restorations [36]. Although composites are less wear-resistant than metals or ceramics, advancements in composite formulations have improved their durability. However, composites can wear over time, particularly under heavy occlusal forces [37]. Despite progress in resin technology, the adverse differential wear of direct resin composites upon contact with opposing teeth and restorative materials continues to be a significant issue, especially for patients experiencing wear. Therefore, a reasonable service period of such restorations is suggested 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 assess the durability, wear resistance, and ability of the material to maintain its shape and function over time. Using these techniques, dental researchers can gather valuable data on the longevity, performance, and safety of different restorative materials, which can help guide the selection of appropriate materials for specific clinical situations [40]. Wear of hard dental tissues and dental reconstructions can be measured *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 for accurate diagnosis.

Many *in vitro* laboratory test methods have been developed by researchers [41-44]. These devices have been created under laboratory conditions to test 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 maintain the definability of the testing conditions [40]. Most devices are used for two-body wear tests, which simulate the contact of teeth without the presence of a third body, such as food. However, food components are also important in controlling wear mechanisms depending on their hardness during chewing [45]. Therefore, some devices have already been adapted to add food as a third body to simulate the chewing system.

#### 3.1. Clinical-based (*in vivo*) evaluation and monitoring techniques

These techniques in restorative dentistry involve evaluating the performance of dental materials under 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 in controlled environments, clinical wear evaluations focus on observing how materials behave under the natural, dynamic conditions of the oral cavity. Many approaches and techniques have been developed to evaluate or monitor wear inside a patient's mouth over time.

**Qualitative methods:** Dentists examine 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 on direct visual inspection of the lesions. While these data are valuable for epidemiological research, comparing

the results can be challenging because of the absence of standardization among evaluators [47,48]. Therefore, these indices are characterized 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 because of the necessity of working casts and laboratory technologies that are not readily available. Furthermore, they are less convenient for clinicians when 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 use of intraoral or extraoral scanners [50]. Techniques such as intraoral cameras and digital scanners can 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-based) wear test techniques

Many devices have been developed for wear testing of hard dental tissues and dental materials under laboratory conditions [54]. 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 tests. However, this only simulates tooth contact without the presence of food. During chewing, food components are important for the wear mechanism, depending on their hardness. Consequently, certain testers have been modified to incorporate a third component, which is the food sample for wear tests [40].

**Simulated mastication tests:** These tests involve the use of 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].

**Jaw simulators:** These 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 by dental students, professionals, and researchers. The 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 facilitated movement along the vertical axis, whereas the second motor enabled movement along the horizontal axis. Both motors were controlled by a computer to precisely mimic the physiological movements associated with chewing. Users can customize the bite strength and number of cycles. Additionally, the device includes an artificial oral environment. This includes the possibility of temperature setting, similar to the human body. Artificial saliva and/or food samples can also be added for more realistic simulations.

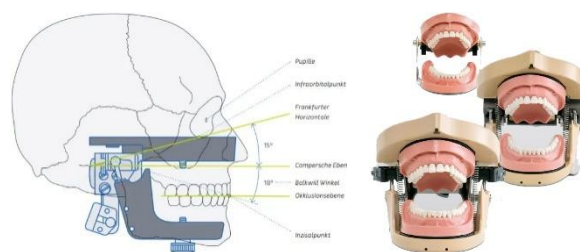
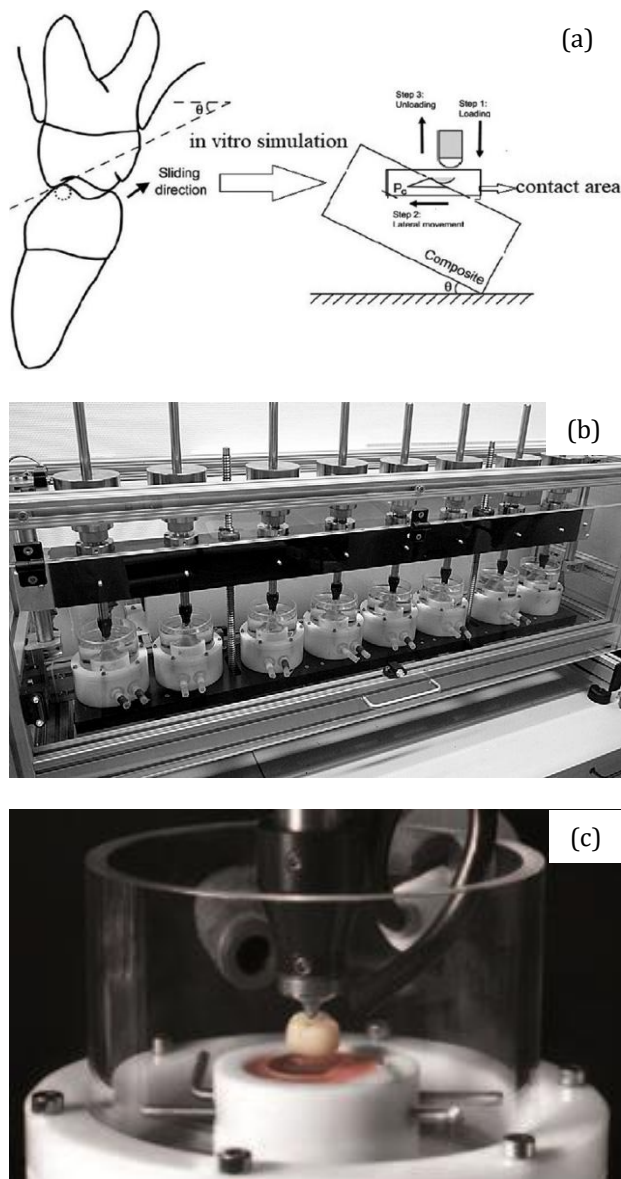


Fig. 6. Jaw simulators [58].

**Chewing simulators:** Chewing simulators are 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 for 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.

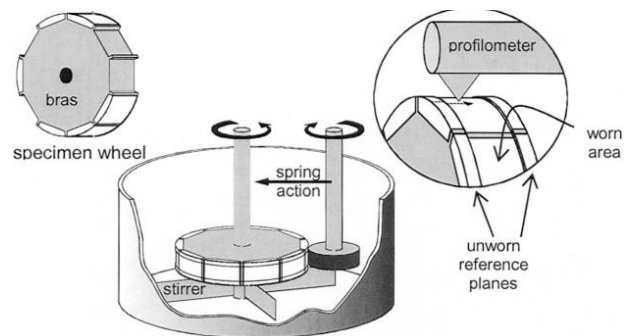
It can conduct two-body and three-body abrasive wear and thermal fatigue tests on teeth, tooth implants, and composite restorative materials. Chewing simulators may have different modes, such as cyclic, wear, and chewing. Wear parameters such as chewing force, tooth sliding distance, thermal change, food abrasiveness, saliva lubrication, and behavior of antagonist materials can be investigated [60,61]. The simulator can accommodate many samples simultaneously with 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.



**Fig. 7.** (a) Schematic of the dual-axis sliding wear simulation test mechanism for the in vitro laboratory chewing cycle test simulation [62]. (b)-(c) Chewing simulator with multiple testing stations and 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 restorative dentistry by providing a controlled and reproducible environment for testing and evaluating the performance of dental materials under conditions that mimic natural chewing [64]. This understanding aids in comprehending how dental materials respond to mechanical and environmental stresses, contributing to innovations in restorative materials and techniques.

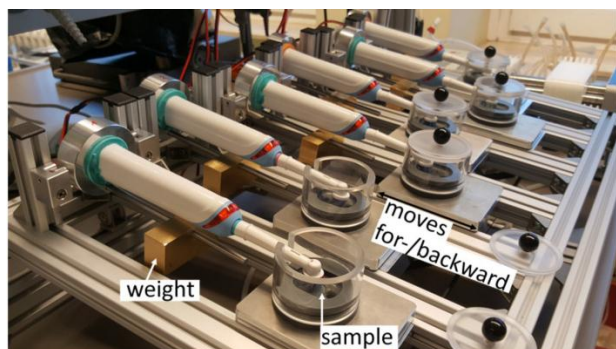
The simulator was designed to replicate the physical forces and movements that occur in the human mouth during mastication, allowing controlled wear testing of dental materials such as fillings, crowns, and other restorations [65]. The test samples were positioned around the edge of one wheel, while the opposing wheel acted as the antagonist (Fig. 8). The force exerted when the two wheels met was set to 15 N. Both wheels were 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 profilometer.



**Fig. 8.** Schematic illustration of academic Center for Dentistry Amsterdam (ACTA) wear simulator [64].

**Toothbrush abrasion tests:** The wear of hard dental tissues and dental materials occurs not only during chewing of food, but also during tooth brushing. The size of such wear in patients depends on many factors, such as tooth brushing technique and frequency, hardness of toothbrush bristles, dexterity of the patient, and the toothpaste used [40,66]. Toothbrush abrasion testers simulate tooth brushing to assess the wear of restorative

materials under simulated conditions of regular brushing [67-69]. This method uses a toothbrush that cyclically linearly moves on the surface of the tested material with an 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, such as toothpaste or only abrasive particles of toothpaste, for a true simulation.



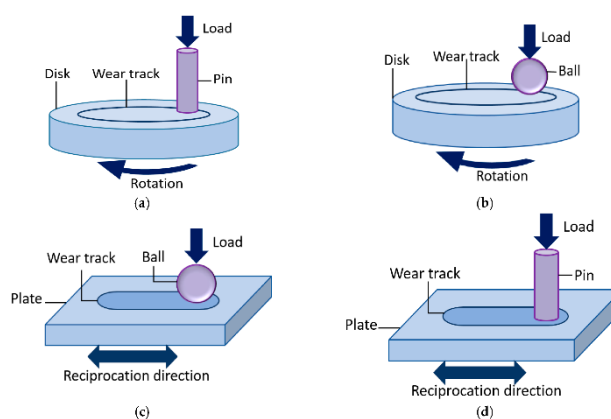
**Fig. 9.** A lateral view of the tooth brushing simulation device [71,72].

**Abrasive slurry tests:** Abrasive slurry tests in dentistry are laboratory tests 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 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 the resistance of a material to abrasive forces over time [73,74].

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

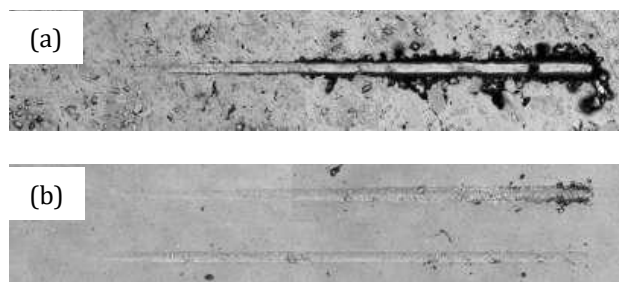
**Pin-on-disc/Ball-on-disc tests:** Pin-on-disc-type tribometers are commonly used to evaluate the friction behavior and wear resistance of materials used in different applications where tribological actions are

operative. This test is preferred because of its simplicity, standardization, and cost efficiency. However, this test technique has some limitations in dental applications. The test device does not accurately replicate the 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 the conditions in the oral cavity [57]. However, it is possible to adjust various parameters, such as the pressing force, rotational speed, and number of cycles, to adapt to oral conditions. It is also possible to include a third component of wear-abrasive food particles in distilled water or artificial saliva to create more realistic test conditions for chewing [45].



**Fig. 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].

**Scratch test:** In this technique, a scratch is made on the tooth surface using a scalpel blade. The disappearance or diminishing of the scratch over time indicates that erosion has occurred. Serial color photographs can also be used to compare changes in enamel translucency and the 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 the influence of the material homogeneity on the test using microscopic imaging, such as a confocal laser scanning microscope. In the scratch test, three distinct types of cracks were identified as they developed from both the surface and subsurface: radial, median, and lateral cracks. Crack propagation reduces the strength of the material [77]. Two examples of scratches formed during scratch tests are shown in Fig. 11 for amalgam and composite materials used in restorative dentistry.



**Fig. 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 the use of nanofillers, the terms microhardness and nanohardness were introduced in operative dentistry. A nanoindenter measures the hardness and elastic modulus of a material on an extremely small surface scale of 50 nm [78]. Nanohardness is generally defined as the resistance of a material to permanent or plastic deformation at the nano-micro level. This test focuses on the research of the physical properties of materials, 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, respectively. The test was performed by applying pressure to a diamond tip with a defined shape into the sample materials. The advantage of this method is that it allows the testing of small samples without their destruction. However, the test is sensitive to sample homogeneity and surface roughness. Therefore, several indentations are made within one sample, and they are consequently evaluated separately [79,80]. Measuring the hardness and elastic modulus is currently the most effective method for comparing dental materials and predicting their wear rates.

### 3.3. Secondary characterization techniques after wear tests

In the context of dental materials, secondary investigation or characterization techniques are used to analyze the wear properties and performance of dental materials following simulated wear tests. These tests help evaluate the material's durability, wear resistance, and overall behavior under oral conditions. These techniques provide in-depth information on the effects of wear on dental materials, allowing researchers and clinicians to make better-

informed decisions regarding material performance, longevity, and suitability for clinical use.

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

**Energy dispersive X-ray spectroscopy (EDX or EDS):** EDS or EDX coupled with SEM analyzes the elemental composition 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 surface contamination or material degradation. In EDX analysis, an electron beam is directed across the sample to create an image that represents 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 sample surface. However, elements with atomic numbers lower than 11 are challenging to detect using EDX [83].

**X-ray diffraction (XRD):** XRD is used to analyze the diffraction patterns of X-rays interacting with the crystalline structure of the material. XRD is used to examine any crystallographic changes in the material after wear tests. This helps identify phase changes in the material that may affect its wear resistance.

**Fourier-transform infrared spectroscopy (FTIR):** FTIR detects the absorption of infrared light by the molecular bonds of a material and provides information on the chemical changes

after wear. This helps identify any chemical degradation, oxidation, or polymerization changes that may have occurred during wear testing.

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

**Wear debris investigations:** The impact of wear debris has been studied in several disciplines. This is addressed in dental in-vitro wear studies [86,87]. Wear debris in dentistry refers to tiny particles or fragments 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 a material before and after wear tests. A microhardness indenter is used to apply a small force to the surface of the material and measure the indentation depth. Hardness is a key indicator of wear resistance. Changes in microhardness can reveal how the surface properties of a material are altered by 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 material loss. This helps assess how the material surface has changed after wear and whether it is still suitable for long-term use [45]. Surface topography refers to the three-dimensional features of a surface that can be analyzed and displayed using optical profilometers (OPs) [81]. These devices provide a non-contact approach for obtaining 3D measurements of a surface.

Mechanical profilometers, designed specifically for two-dimensional measurements, operate by systematically 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  $\mu\text{m}$  [89].

## **4. STRATEGIES FOR MINIMIZING 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 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 the posterior teeth. It is 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 further tooth damage. This approach should also focus on enhancing adhesive bonding and, when feasible, promoting remineralization of the remaining tooth structure [90].

### **4.2. Occlusal management**

Managing occlusion is crucial for preventing excessive wear. In cases 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 and the wear properties of the material. Materials with higher wear resistance should be considered for the treatment of high-stress areas, such as the posterior region, whereas aesthetic considerations may guide the use of composites and ceramics in the anterior regions.

The use of composite resin offers a clinical benefit by facilitating the patient's adaptation to occlusal changes while 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 wear potential. Restorative materials should be polished after placement, and patients should be educated about maintaining a smooth surface by avoiding abrasive toothpaste and hard-bristled brushes [45,88].

### **4.5. Prevention of erosion**

Patients should be advised to limit their 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, and habit change may also help to remineralize enamel and reduce the effects of erosion. In the case of bulimia or reflux diseases, patients can apply to a medical doctor for treatment [91].

### **4.6. Regular monitoring**

Regular dental checkups and monitoring of wear patterns are essential for early intervention. Digital imaging and occlusal analysis can help detect wear and assess the condition of the restorations and natural teeth. In addition, several clinical indices can be used to monitor the progression of tooth surface loss [91]. Patient education is critical for 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 a deeper comprehension of specific occlusal principles have led to the adoption of a minimally invasive approach as the preferred choice [92]. In the last 50 years, dentistry has witnessed numerous important advancements. These developments have led to enhanced knowledge and comprehension of dental adhesion, materials, and principles of clinical occlusion [93]. Developments in the application of digital technology in clinical settings have also occurred. Each of these factors impacts 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 the effect of tooth wear on a patient's quality of life [92-94]. 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 wear dynamics, the industry is 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 of patients.

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

### **5.1. New trends in restorative biomaterials**

The implementation of restorative care for patients experiencing tooth wear can be enhanced by using CAD/CAM technology. The development of advanced dental materials with improved mechanical and adhesive characteristics may enable treatment with minimal intervention. This advancement could also allow a greater number of patients to receive the necessary care reliably within a primary care environment. An example is the recent introduction of polymer-infiltrated ceramic network (PICN) materials, which are hybrid ceramics that combine the desirable

mechanical, physical, and aesthetic properties of both ceramics and composites. PICN materials can be used to restore worn teeth using CAD/CAM without the need for tooth preparation [92].

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].

## **5.2. Digitalization in dentistry**

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

## **5.3. Minimally invasive procedures**

Dentistry is shifting toward 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 preserve the natural tooth structure. Protective coatings and sealants have become more effective in preventing or reducing wear on teeth and dental restorations [99,100]. These materials can be applied to minimize damage from abrasion or acidic foods and drinks.

## **5.4. Wear impact on restorative materials**

With a 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 to 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 to address this growing problem.

## **5.5. Personalized dentistry**

Tailored strategies may exist for addressing dental wear, considering 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 to the teeth. With advancements in digital impressions, restorations can be designed more precisely, reducing stress on individual teeth and limiting excessive wear.

## **5.6. Sustainability and environmental concerns**

As the emphasis on sustainability grows worldwide, future dental materials will likely be developed with environmental factors considered. This could lead to 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 may include wearable devices or smart sensors that can be integrated into dental restorations or orthodontic appliances. These sensors can provide real-time data on the extent of wear, enabling quicker adjustments and preventive actions.

## 5.8. Patient education

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

## 5.9. Nanotechnology

Nanotechnology has led to significant advancements in various fields, including medicine, dentistry, and manufacturing. In a few years, the basic science of nanotechnology will change dental practice. By utilizing nanoscale materials and technologies, nanotechnology enables advancements in the 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 with existing materials.

## 6. CONCLUSIONS

Wear in restorative dentistry remains a complex and multifactorial phenomenon that critically affects both natural teeth and restorative biomaterials. 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 the progressive deterioration of both natural dental tissues and restorative materials. An ideal restorative biomaterial 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 optimization of clinical outcomes. However, limitations still exist in replicating the full complexity of the oral environment of the human body. 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 on wear mechanisms and continued innovation in restorative materials will be essential to improve long-term clinical success and patient quality of life.

**Acknowledgement:** This study, titled *Wear in Restorative Dentistry/Teeth and Dental Materials*, was presented at the SerbiaTrib 2025 International Conference on Tribology, held in Kragujevac, Serbia.

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