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Research Article

Micro-scratch and wear resistance of restorative dental materials: an in vitro study

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Abstract

Aim: The study of the tribological properties of dental materials is a growing and rapidly expanding field. The aim of our research is to investigate the micro-scratch and wear resistance of different restorative dental materials.

Materials and methods: Three restorative materials indicated for the treatment of dental caries in the distal area of the dentition were used: dental amalgam without γ_2 phase, with high Ag content (Cavex Non Gamma-2); a microhybrid resin-based composite material (Gradia Direct posterior); a metal alloy (Duceralloy C) was used as a positive control. All specimens were subjected to micro-scratch resistance test in 1 N, 5 N, 9 N mode, a ball-on-flat wear resistance test at 120,000/240,000 cycles loaded at 50 N. The examined surfaces of the specimens were visualized by optical microscopy and by 3D profilometry of all the specimens tested after 240,000 wear cycles.

Results: The results are presented in the form of graphs - for each specimen, for each individual test, and for each individual cycle. The wear resistance of Duceralloy C increases after 240,000 cycles. The wear resistance of Cavex Non Gamma-2 and Gradia Direct posterior decreases with increasing time and friction cycles.

Conclusion: The results of this study may help to elucidate the wear mechanisms and provide additional information on the expected changes in the materials tested in clinical practice.

Keywords

3D profilometry, ball-on-flat test, dental tribology, micro-scratch test, restorative dental materials, micro-scratch test

Introduction

Tribology is the science and engineering of interactive surfaces, involving the study and application of the principles of friction, lubrication and wear.[1] Tribological studies range from theoretical to experimental and from basic to applied research, covering aspects from the nano- to the microscopic world.[2] The examination of the tribological properties of dental materials is a growing and rapidly expanding field. Intensive research has been carried out to understand the importance and applicability of dental tribology for the selection of dental materials for the treatment of carious lesions in a high-stress region.[3]

It is recognized that tooth wear is a clinical problem that is becoming increasingly important in ageing populations. The frequency of parafunctional patients in the world population has increased. According to most literature sources, the prevalence of adults exhibiting some periods of bruxism ranges from 6% to 20%.[4]

The main problem involved in the dental application of resin-based composite materials is their inadequate wear resistance when used as posterior composite restorations under extreme masticatory forces.[5] Despite improvements in the mechanical properties of composite resins, wear is still a major problem, especially in patients with parafunctional activities.[6]

Aim

The objective of our research is to study the micro-scratch and wear resistance of different restorative dental materials.

The working hypothesis for this study was that the three restorative dental materials would exhibit different tribological behavior, with the metal alloy (control) having the highest wear and scratch resistance and the resin-based composite having the lowest.

Materials and methods

Three restorative dental materials were used: a dental amalgam without γ_2 phase, with a high Ag content (Cavex Non Gamma-2); a microhybrid resin-based composite material (Gradia Direct Posterior); a metal alloy (Duceralloy C) was used as a positive control. The test materials are indicated for distal restorations in operative dentistry.

An original experimental model was used for the purposes of the present study. Its preparation has already been described in our previous research.[7] Metal plates measuring 50×50 mm and 3 mm thick were manufactured as standard carriers. Each was sliced into 9 holes measuring 10 mm in diameter and 1.5 mm in depth. The corresponding test substance was applied to the apertures.

The retention of the composite test materials in the cut-out sockets of the metal plates was further reinforced by the metal primer (Metal Primer-2, GC Corporation, Tokyo, Japan). Composite specimens were cured incrementally with an LED light unit (Mini LED Satelec, Switzerland), then finished and polished with fine-grit.

Dental amalgam capsules were mixed in duration and frequency in accordance with the manufacturer's recommendations. Dental amalgam was placed and condensed according to well known methods. The amalgam samples were polished after 24 hours of settling.

Positive control group specimens were made and cast from a metal alloy containing no nickel. The fixation of the metal alloy control tribological discs was performed by means of a prepared matrix form of additive silicone (Ormaplus, Major, Italy). The parameters of the standard metal plate were used. Using an epoxy resin prepared according to the manufacturer's requirements, metal test discs of the control study were fixed. The composition of Duceralloy C included Co (59.4%), Cr (24.5%), W (10%), Nb (2%), V (2%), Si (1%), Mo (1%), Fe (0.1%). This composition provides high hardness and corrosion resistance.

The design of the study **(Fig. 1)** is identical to that of our previous paper.[7] For each material type, the three specimens from the first column are tested for scratch resistance in the 1 N, 5 N, and 9 N mode. The three specimens from the second column are tested for ball-on-flat friction resistance for 120,000 cycles at 50 N load. The three specimens from the last column are tested for ball-on-flat friction resistance for 240,000 cycles at 50 N load.

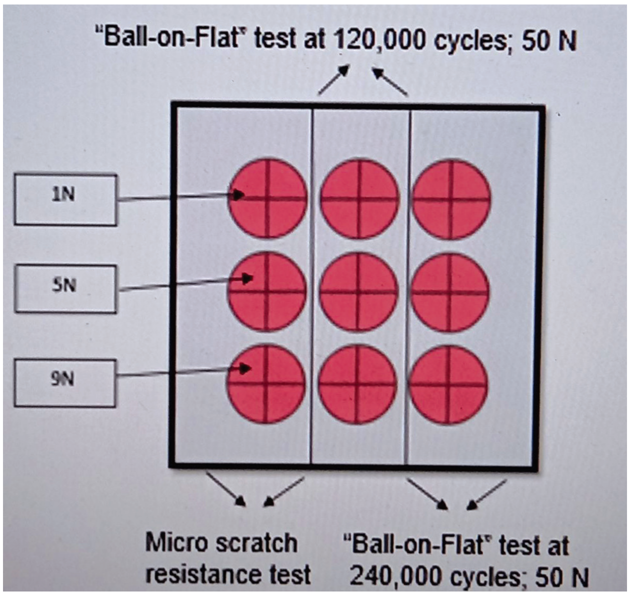


Figure 1. Design of the study

As in our previous study[7], the test instrument used in this investigation is UMT-2M (Bruker-CETR) **(Fig. 2)**. This universal modular device can perform a wide range of macro- and micro-mechanical and tribological tests on coatings (thin or thick, hard or soft) and bulk materials such as ceramics, polymers, glass, composites, fabrics, and paper. It operates with loads from 5 mN to 1000 N, allows the use of multiple sensors and provides simultaneous measurement, visualisation and real-time recording of deformations and forces while performing synchronized linear and rotary displacements in different axes using a synchronized linear or rotary drive. A servo control mechanism is used to achieve high precision motion and load control.

The mode and conditions of the micro-scratch test procedure included a cycle of three steps in which multiple scratches were performed with a distance of 1 mm between each two scratches, and the length of each scratch was 5 mm. The test was performed with three constant forces (1 N, 5 N, and 9 N) for each of the five samples. The translational movement of the scratch was performed by a linear drive on which the samples were fixed at a speed of 0.1 mm/sec. The lateral movement of 1 mm distance when performing successive scratches was realized by a slider that moved the head with the cutter. The tests were carried out in accordance with the ASTM G133-95 standard.

The ball-on-flat wear tests used a 6.35 mm diameter chromium-plated steel ball, which was slid over the surface of a fixed specimen under the influence of a reciprocating motion of a linear actuator. The apparatus monitors and records the dynamic normal load, frictional force, and co-

Figure 2. UMT-2M (Bruker-CETR)

efficient of friction.

Tests to determine the coefficient of friction of dental samples were carried out under the same conditions and in accordance with the standards as follows:

- speed of ball movement on the surface: 2.5 mm/sec;
- applied constant force: 50 N;
- friction test duration: 2 times for 30 minutes;
- temperature of 24°C;
- humidity: 40%.

3D profilometry was performed using a Zeta-20 optical 3D profilometer (Zeta Instruments) with vertical (Z) resolution <1 nm, field of view from 0.006 mm^2 to 15 mm^2 and magnifications of 5×, 20×, 50×, and 100×.

Data were analyzed with IBM SPSS Statistics for Windows, version 27.0 (IBM Corp., Armonk, NY, USA). Statistical analysis was performed using descriptive statistics (mean ± *SD*). Comparisons between groups were made using one-way ANOVA, with $p<0.05$ considered significant.

Results

Table 1 displays the micro-scratch test average results.

The results of the micro-scratch tests are presented by graphs for each specimen, and for each individual test **(Fig. 3)**

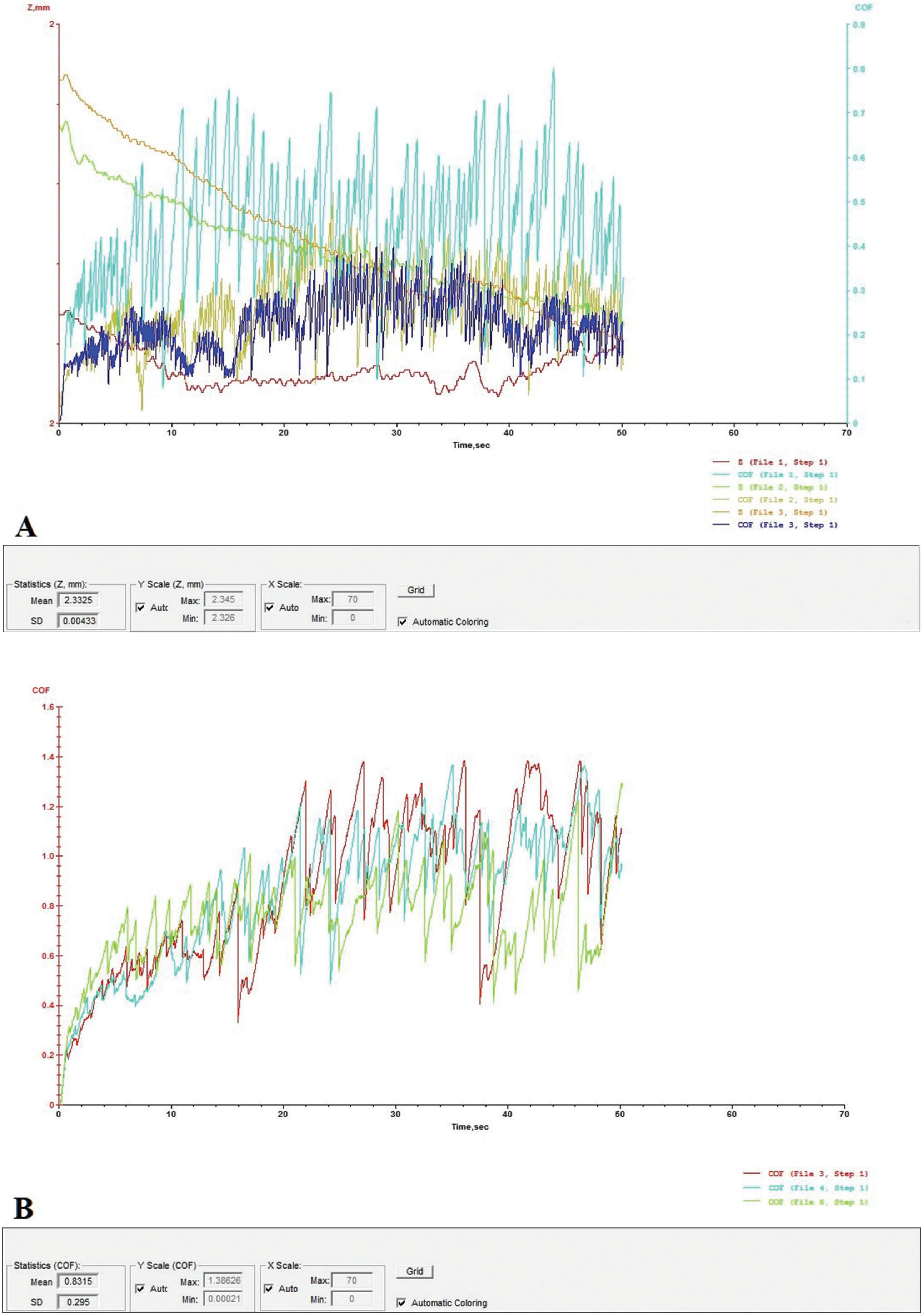
As shown in **Table 1**, the metal alloy (Duceralloy C) presented the lowest coefficient of friction at low loads, though with higher scratch depth at 1 N compared to the amalgam. Cavex Non Gamma-2 demonstrated the shallowest scratch depths, while Gradia Direct Posterior exhibited consistently higher friction coefficients, peaking at 9 N. **Fig. 3** illustrates these results, showing more stable performance for the alloy than the composite.

The results of the wear resistance tests for each sample as well as for each individual test and each individual cycle of each test are also presented graphically **(Fig. 4)**. **Fig. 4** shows the wear resistance trends: the composite showed progressive degradation across cycles, the amalgam intermediate resistance, and the alloy improved resistance over time, likely due to friction-induced hardening.

From **Table 2** it can be summarized that the micro-scratch depth values of the positive control Duceralloy C after the first 30 minutes (120,000 cycles) of wear are higher than those after the second 30 minutes (240,000 cycles). For the Cavex Non Gamma-2 specimen tested, the wear resistance decreased over time. The micro-hybrid composite showed a lower wear resistance, which decreased with increasing time and friction cycles (13 µm after 30 min/120,000 cycles; 18 µm after 60 min/240,000 cycles).

Table 1. Average values for the coefficient of friction and the depth of the micro-scratches as a function of the load applied

Samples	Dental material	Load (N)	Coefficient of friction	Depth of micro-scratch (µm)
1	Duceralloy C	1	0.3347	46.79
		5	0.5097	26.54
		9	0.7307	51.76
3	Gradia Direct Posterior	1	0.4953	30.71
		5	0.7599	28.21
		9	0.8315	40.23
4	Cavex Alloy	1	0.1883	7.66
		5	0.3213	14.29
		9	0.5412	20.11



Z,mm
COF
Time,sec
S (File 1, Step 1)
COF (File 1, Step 1)
S (File 2, Step 1)
COF (File 2, Step 1)
S (File 3, Step 1)
COF (File 3, Step 1)
A
Statistics (Z, mm):
Mean 2.3325
SD 0.00433
Y Scale (Z, mm)
Autc
Max: 2.345
Min: 2.326
X Scale:
Auto
Max: 70
Min: 0
Grid
Automatic Coloring
COF
Time,sec
COF (File 3, Step 1)
COF (File 4, Step 1)
COF (File 6, Step 1)
B
Statistics (COF):
Mean 0.8315
SD 0.295
Y Scale (COF)
Autc
Max: 1.38626
Min: 0.00021
X Scale:
Auto
Max: 70
Min: 0
Grid
Automatic Coloring

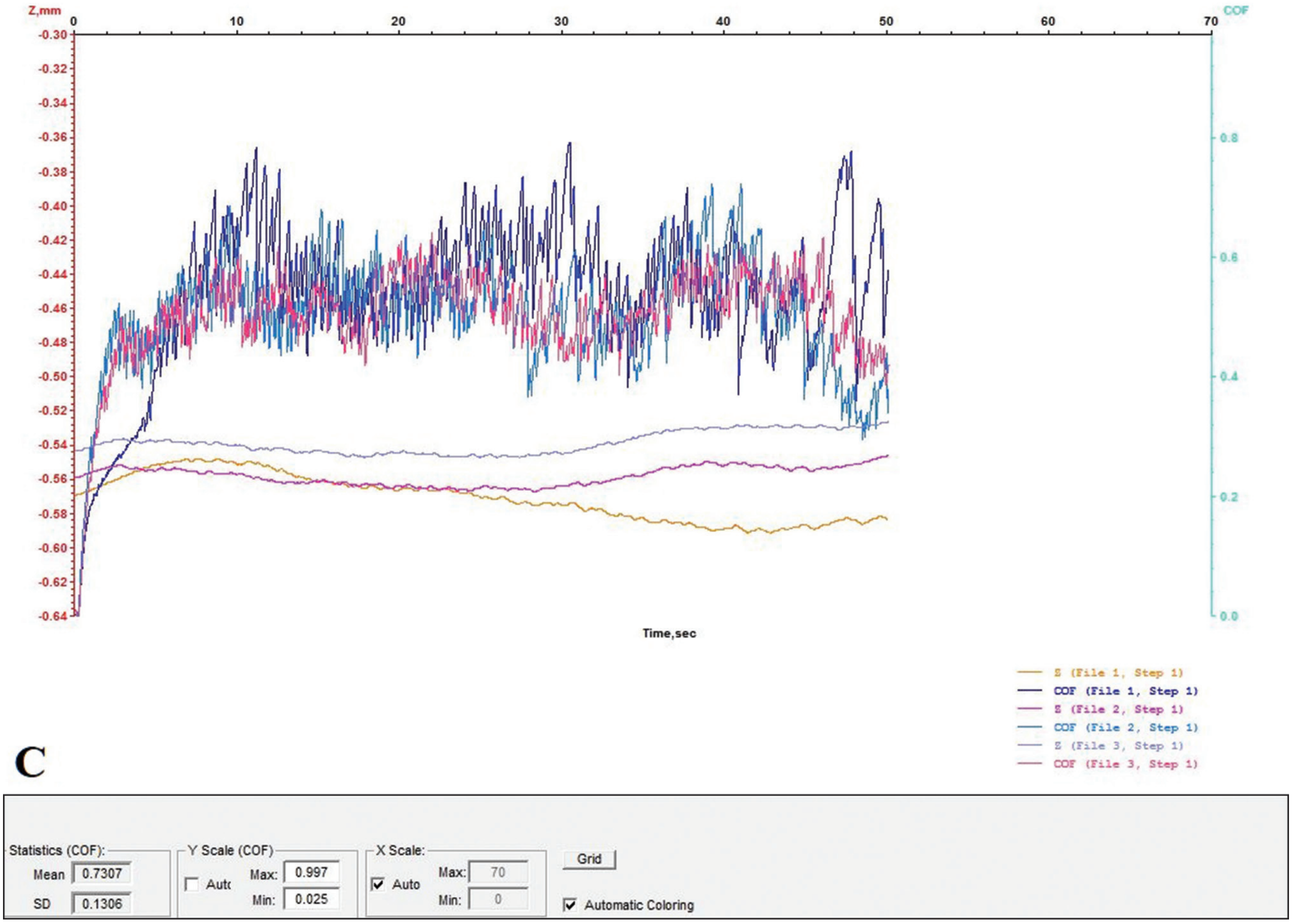
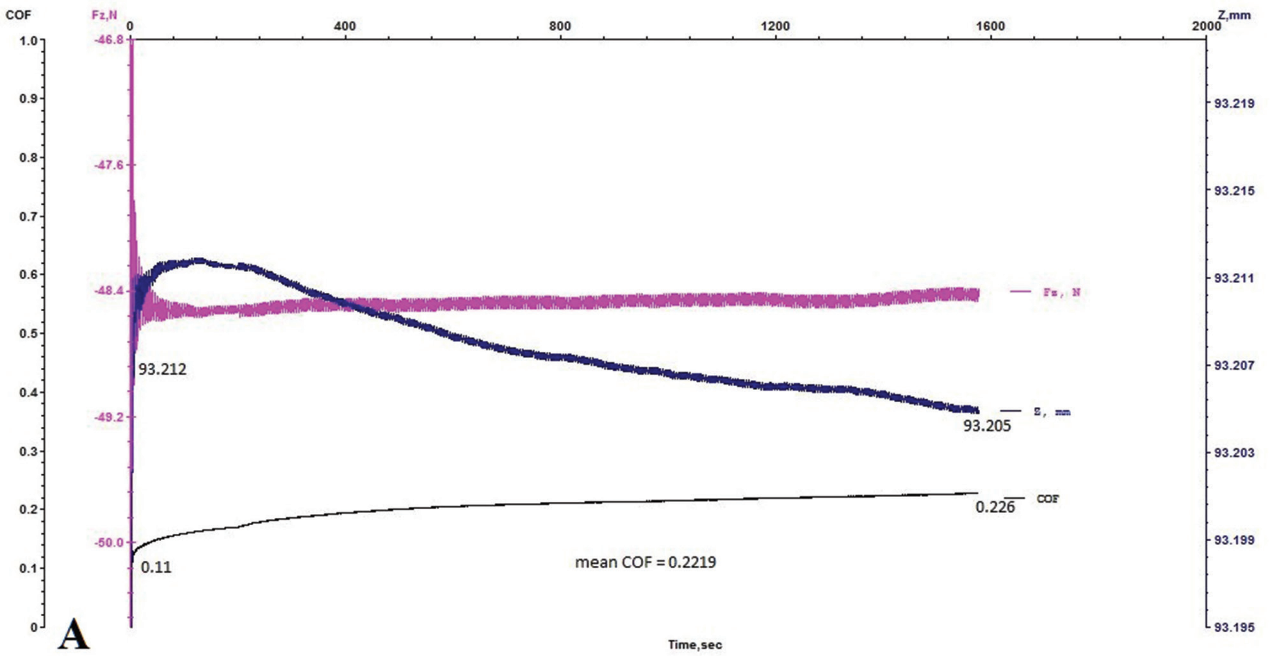


Figure 3. Graphical representation of coefficient of friction and depth of micro-scratch results from three consecutive tests in the same direction. Applied force of 9 N; speed of 0.1 mm/sec, and scratch length of 5 mm; **A**. Cavex Non Gamma-2; **B**. Gradia Direct Posterior; **C**. Duceralloy C.



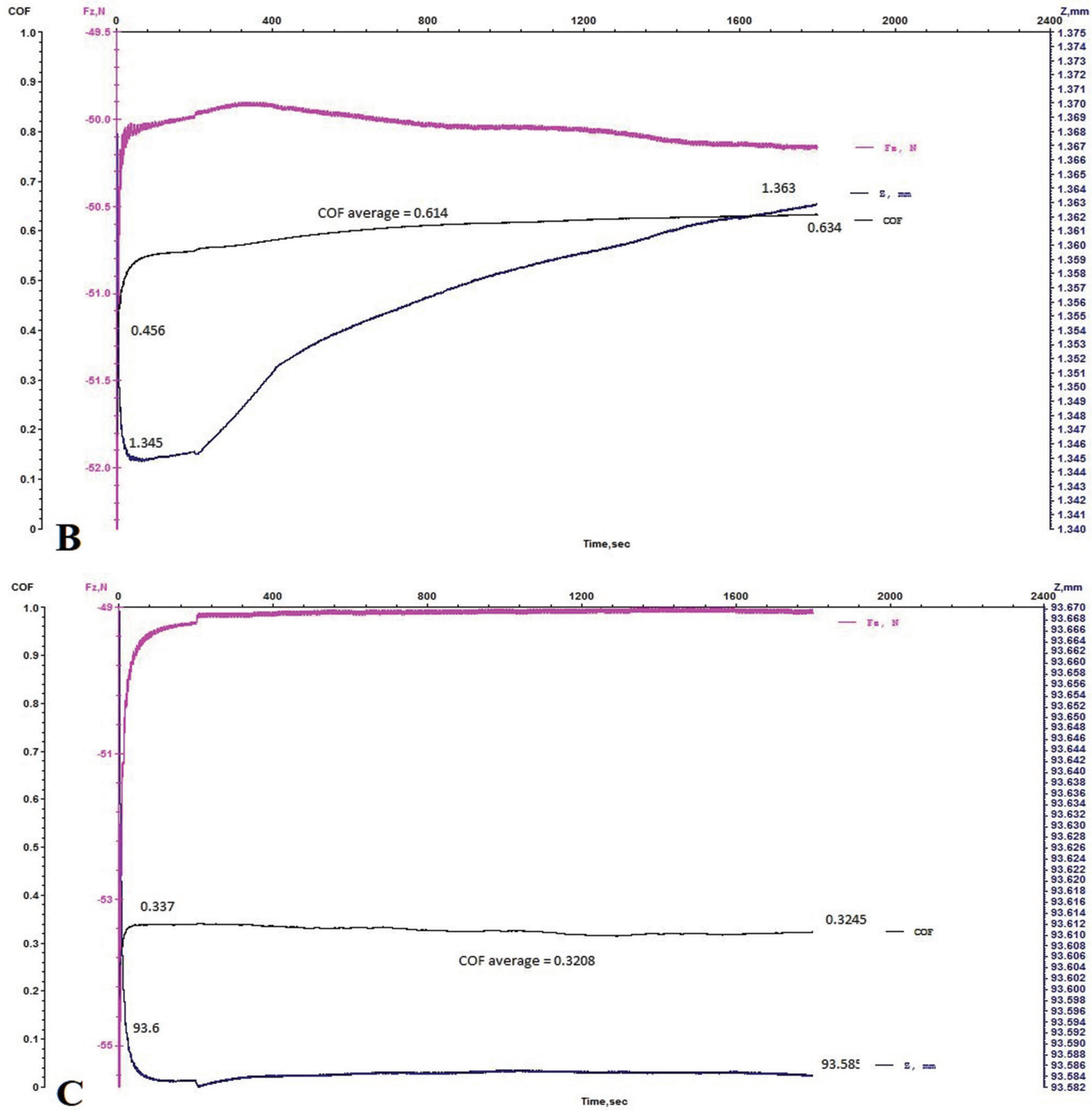


Figure 4. Graphic representation of the reported results during the second 30 minutes of the ball-on-flat test; **A**. Cavex Non Gamma-2; **B**. Gradia Direct Posterior; **C**. Duceralloy C

Table 2. Average values for the coefficient of friction and the depth of micro-scrach for each of the two 30-minute wear cycles for each specimen

Samples	Dental material	Load (N)	Average coefficient of friction	Depth of micro-scratch (μм)
1	Duceralloy C	50	0.3568	8
		50	0.3208	1.5
2	Cavex non Gamma-2	50	0.1619	4
		50	0.2219	7
3	Gradia Direct Posterior	50	0.5501	13
		50	0.614	18

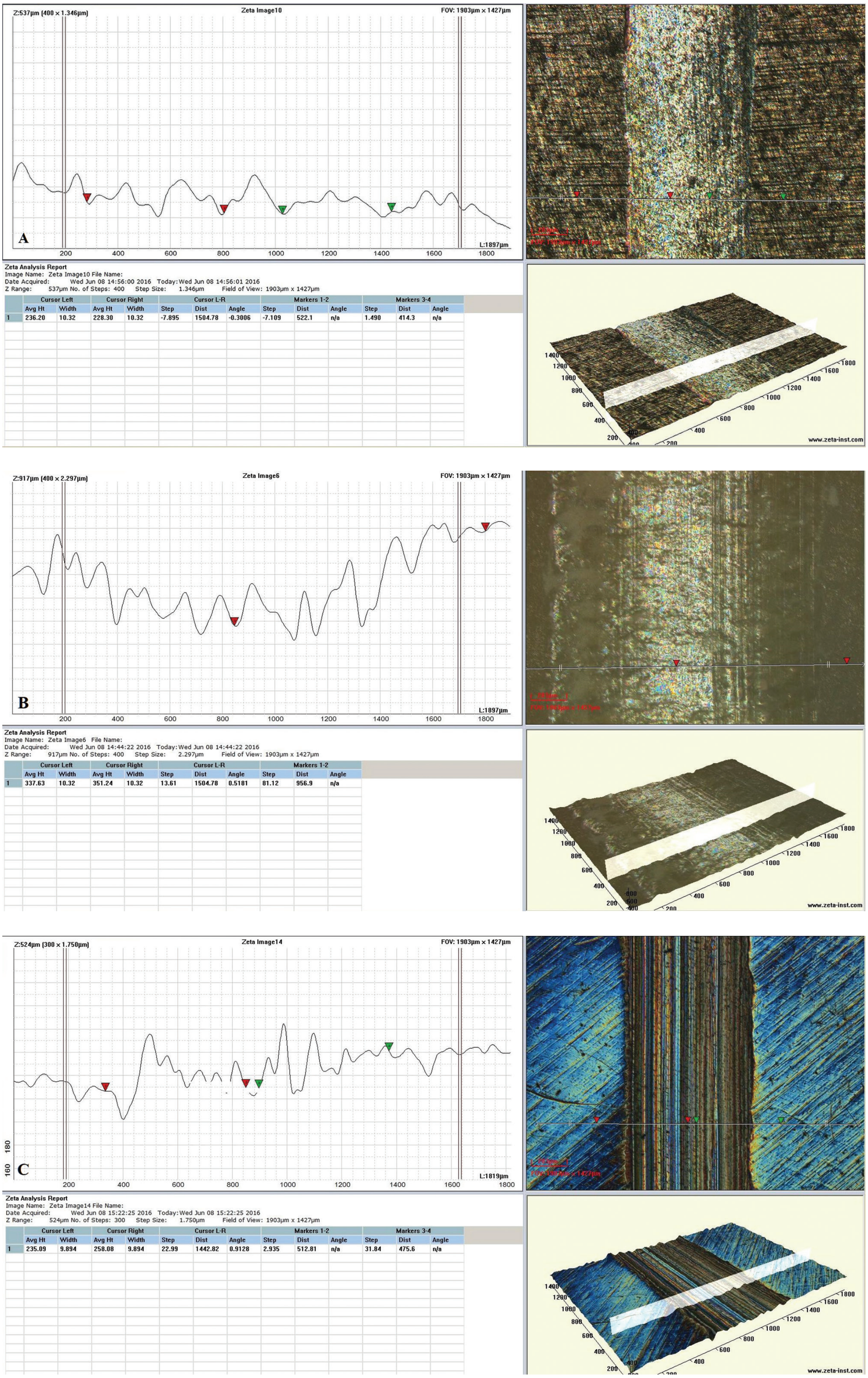


Figure 5. 3D profilometry; **A**. Cavex Non Gamma-2; **B**. Gradia Direct Posterior; **C**. Duceralloy C.

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The examined surfaces of the test specimens were visualised by optical microscopy after micro-scratch and friction testing and by 3D profilometry of all test specimens after 240,000 wear cycles **(Fig. 5)**.

Due to the high hardness and homogeneous composition of the metal control, these samples exhibit a pronounced but uniform surface roughness. In the dental amalgam samples tested, the surface roughness is less pronounced, since the amalgam is softer than the metal, but micropores are observed due to the phase crystallization. Despite the inorganic phases, each of them has a different hardness and wear resistance. Insufficient condensation and polishing in the test specimens' preparation is another probable reason for micropores. The Ag percentage in the composition of Cavex Non Gamma-2 is significantly higher. This is due to the more uniform surface roughness, which is close to that of the metal control. The surface roughness of the resin-based composite studied is less pronounced than that of the metal alloy. It has multiple micropores. The logical explanation for this is the fact that it is composed of two different natural phases, organic and inorganic, which have very different mechanical properties.

Discussion

In tribology, the surface of a body is defined as the interface of the body with the environment, which differs in structure and properties from those of its internal parts. The quality of surfaces largely determines functional characteristics such as fatigue, wear resistance, friction, and corrosion resistance of materials, which in turn determine the indications for their use. The surface roughness of direct composite restorations is important for their durability as it reflects the interaction of the restorative materials with the oral environment. Rough, unpolished restorations increase the coefficient of friction and can increase the rate of wear.[8]

The results obtained indicate a high roughness of the specimens tested. It can be concluded that in clinical conditions, it is even more difficult to achieve optimal smoothness of the surface of restorations. This affects their mechanical behaviour, especially under conditions of extreme masticatory forces. A large number of laboratory studies on the wear resistance of dental restorative materials are described in the available specialised scientific database.[9-13] In these studies, various types of devices were used to simulate tooth wear with the participation of two bodies (two-body wear) or with the participation of three bodies (three-body wear). With the help of these devices, the conditions in the oral cavity are reproduced as closely as possible. Potentially, materials such as enamel, gold, ceramics, composites, that simulate the in vitro antagonist, can be used.

No data were found for the study of the wear resistance of dental restorative materials with the measuring device we used – UMT-2M (Bruker-CETR), which by its nature is not an instrument for simulating tooth wear, but a universal modular instrument for tribological testing. This measuring device is used in scientific research on various materials such as ceramics, metals, polymers, glass, composites, which are not used for dental purposes.[14,15] The results obtained in the course of our study are not comparable with the laboratory tests cited in the dental scientific literature, due to the specific measuring equipment and the differences in methodology (load force, number of cycles, duration).

In our previous research, we found an analogy with scientific research on the tribological properties of polymer-based materials, which are not applied in the dental field.[7,14,15]

The observed improvement in wear resistance of the metal alloy during prolonged testing may be explained by friction-induced temperature rise, which leads to surface hardening of the alloy. This phenomenon has been described in tribological studies of metal alloys and is consistent with our findings.[16]

3D profilometry is a fast, non-contact and objective method that provides information about the topography and roughness of the objects under investigation. It can be used to obtain both topographic and quantitative data, which explains its wide application in a number of medical fields. In dentistry, 3D profilometry is mainly used to study the abrasion resistance of hard dental tissues and different types of restorative materials such as dental composites, glass-ionomer cements, and dental ceramics.[17]

Conclusions

Within the limitations of this in vitro study, we conclude that material composition and surface roughness significantly affect wear resistance and scratch behavior of restorative dental materials. The metal alloy demonstrated the highest resistance, followed by the amalgam, while the resin composite showed the least favorable performance. These results emphasize the importance of material selection in clinical situations involving high occlusal stress and parafunctional habits.

There are studies confirming that in vitro wear simulation is extremely valuable in the screening of new restorative dental materials. Results in this area will elucidate the mechanisms of wear and provide additional information on the expected changes in the materials under investigation in clinical practice.

Ethical approval

Not applicable

Ethic al statements

The authors declared that no clinical trials were used in the present study.

The authors declared that no experiments on humans or human tissues were performed for the present study.

The authors declared that no informed consent was obtained from the humans, donors or donors' representatives participating in the study.

The authors declared that no experiments on animals were performed for the present study.

The authors declared that no commercially available immortalized human and animal cell lines were used in the present study.

Conflict of interest

The authors have declared that no competing interests exist.

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Use of AI

No use of AI was reported.

Data availability

All data used are referenced or included in the article.

Author contributions

All authors have contributed equally.

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