fortune Journals

DENTAL RESEARCH AND ORAL HEALTH
ISSN: 2641-7413

Research Article

Analysis state of Tensions and Strains in the structure of the active part material of a Dental Bur and its Failure

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Abstract

The paper aims to assess the wear and damage/failure of a dental bur, addressing the concept of its durability and reliability. A series of elements that underlie the occurrence of the wear and failure phenomenon are highlighted, considering the operating life of dental burs and the conditions imposed by the environment. The paper synthesizes the issues of degradation mechanisms and the effects they have on the active part of dental burs, on dental materials used in dental laboratories. Some theoretical aspects, state of tensions and strains, respectively, functional parameters in the work process were identified, and one of the ways of evaluating the wear and failure of the active part of a dental bur.

Keywords: Dental bur; Wear; Damage/failure; Durability; Reliability

Introduction

Dental engineering is the field of development of industrial branches for the supply of dental medicine. The correct design and quality control of dental instruments and burs represent the main task of this industry. Features such as quality, use safety for patients and operators, mechanical resistance, corrosion, are just a few that should be taken into account when designing dental devices/instruments and burs [1].

Dental burs are small metal cutting tools/instruments used in dentistry (laboratory and dental practice), for various dental operations (cutting hard tissues (bones or teeth), cleaning areas where dental caries occur, creating cavities for the installation or removal of fillings, and making dental crowns [2,3]. These instruments have a series of cutting blades, of different shapes and diameters, appropriate to the role for which they were created [4]; all of them, however, have several common characteristics, namely: the head (active part) of the bur; the neck of the bur; and the body or foot of the bur, figure 1.

Figure 1: Components of a dental bur: the head (active part) -1, the neck - 2, and the foot of the bur - 3

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Citation: Filip Ilie, Dana Alina Baetu. Analysis state of Tensions and Strains in the structure of the active part material of a Dental Bur and its Failure. Dental Research and Oral Health. 9 (2026): 08-16.

Received: April 03, 2026
Accepted: April 16, 2026
Published: April 21, 2026

Any dental bur is included in dental equipment, designed to perform dental operations, by rotational movement in a single direction (clockwise [5]), corresponding to the curvature of the cutting blades, a movement that is given to them by an electric micromotor (Figure 2).

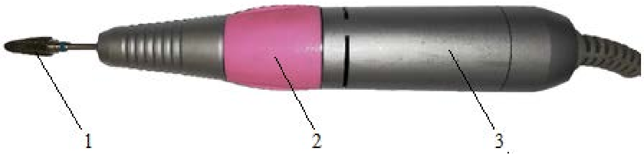

Figure 2: Micromotor equipped with a dental bur: 1 – dental bur; 2 – handle; 3 – electric micromotor

Constructively, dental burs are the same as any hand instrument, the difference being the head of the bur (see position 1 in figures 1 and 2), which is cutting, abrasive, or finishing, and depends on the purpose for which it was made, and the shape and material used in the construction of the active part depend on the working technique.

The head of the dental bur is provided with cutting blades. The greater number of blades, the smoother the prepared surface. Thus, cutting or abrasive dental burs have 4, 6, 8, or 10 blades, and those for finishing have 12, 16, 18, or 30 blades. The blades can be straight or in an axial spiral and both can be manufactured with or without criss-crosses [6].

In general, the geometric aspects of dental burs are made so that they have a negative angle of inclination.

But there are also dental burs with a positive rake angle, mainly designed for the milling of soft materials (e.g., acrylic materials), removing material during milling, and preventing bending of the device/instrument.

When the inclination angle of a bur blade is too high (> 40°), it can damage the tooth substrate, and when the angle of inclination is below 40°, the entire action becomes easier. The service life of the dental bur decreases the sharper the angle of the cutting tips is.

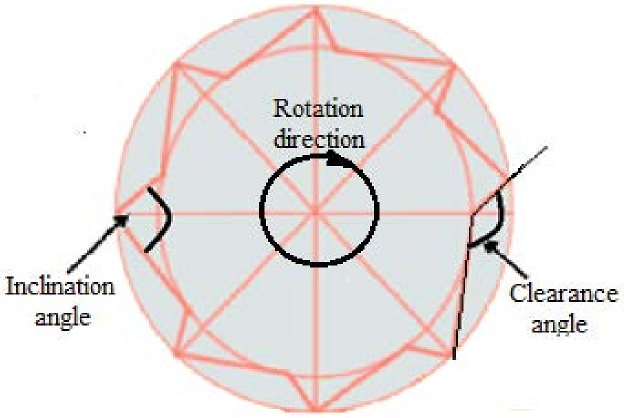

Figure 3: Schematic diagrams of rake and clearance angles relative to the cutting direction.

The neck of the dental bur is the part that connects the head and the foot of the bur and has the role of transmitting movement to the bur head, providing good visibility of the active part, and allowing mobility in handling.

The foot of the dental bur allows fixation, transmission of movement, and centering of the instrument [7,8] and requires calibration according to the micromotor chuck to ensure operation without lateral play or the occurrence of slippage between the foot and the chuck during the work process.

The machining process involves the use of dental burs by rotating at a set speed and then brought into contact with a dental material to be processed. Milling is the result of the simultaneous action of two movements: the rotational movement of the bur and the feed movement (rectilinear and rotational) of the material to be processed [8,9].

The machined surfaces can have different shapes, from flat, cylindrical, profiled, to helical, etc., made by kinematic or programmed commands.

Materials and Methods

Conventional, the dental burs are made of stainless steel, diamond granules or particles, tungsten carbide (WC), and tungsten carbide-cobalt (WC-Co) composite material, with different shapes and sizes depending on the purpose and place of use.

In addition, dental rotary cutting burs, depending on the material of their manufacture, can be made of diamond or metal. Diamond burs are abrasive instruments that consist of three parts: a metal core, diamond filings, and a bonding material. The size of the diamond filings can be different sizes [10,11]. In contrast, metal burs can be made of steel with sharp cutting edges, being suitable for dentin preparation at low speed (but not for enamel preparation), or of WC, which works better regardless of speed, being suitable for both enamel and dentin [10,11].

The most materials used are stainless steel and tungsten carbide (WC) [11-15], each has its advantages and disadvantages specific.

Carbon steel easily corrodes and quickly wears, and therefore, for dental burs, it seems to be an unsuitable material choice. However, the wear rate associated with the milling process is significantly reduced at lower speeds, and steel may be a suitable material [16]. The sterilization process of the dental burs is the main environment of corrosion, but oral conditions also contribute to this [16].

Instead, the stainless steel has a higher corrosion resistance, but the cutting blades are less effective than those of carbon steel. Compared to diamond materials (WC, etc.), stainless steel is a relatively inexpensive material, which makes it suitable for dental burs, provided that it is intended for single use, and dental burs are classified as disposable [13,17].

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WC is characterized by high hardness, and therefore, it is extremely resistant to wear, but it is fragile compared to stainless steels [18]. This recommends that the active part blades of dental burs be made of WC, and the shank can be of steel, and by sintering, the WC blades can be bonded to the steel shaft. Also, WC is suitable for dental burs intended for use several times, but at lower speeds [6,11]. Usually, the instruments made of steel are much cheaper than those of WC, but these (from WC) compensate by increasing their service life [17,18].

Dental burs made of WC contain cobalt (Co) as a binder in percentages of about 6%, which provides these instruments with additional hardness. However, finer-grained WC is harder and provides greater wear resistance.

WC particle size and the WC/Co ratio are the parameters that control the basic properties of the material. The combined, coarse-grained WC and a high Co coefficient provide increased impact and shock resistance [19,20], in general. But greater wear resistance is provided by the finer-grained WC, being harder. Therefore, it is necessary to avoid premature damage in order to have higher durability and to achieve optimal performance [21,22]. The most common causes of damage to dental burs are operation, sterilization, and disinfection [23,24].

The WC–Co composite is similar to ceramics, consisting of WC grains that are mixed with Co and have very good mechanical and physical properties, namely: hardness, fracture, and high temperature resistance, high thermal conductivity, good electrical conductivity, and wear resistance [25-27].

Most dental materials from WC additionally contain a quantity of Co. Depending on the size of the WC particles, which can be sub-micron (0.5 – 0.8 μm) to ultra-fine (0.2 – 0.5 μm), 6 -16 wt. % of Co is added as a binder. The properties of these materials depend on two very important parameters: the WC/Co ratio and the size of the WC particles.

So, to get materials with higher wear resistance, WC with a finer grain size and lower percentage weight of Co can be used [28].

Dental WC burs are precise dental instruments with high cutting capacity and long service life. Taking into account their different shapes, special coatings, and different blade configurations, a variety of dental treatments can be performed with them.

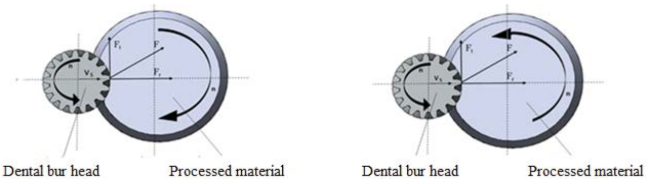
Dental WC-Co mixture burs are most commonly used for crown preparation and cutting, preparation of fillings and roots, including removal of old fillings, root canal, caries removal, bone contouring, etc. [29], and are the subject of research in this paper.

Dental burs made from WC are much more expensive than similar ones made of steel, but they compensate for this with their increased service life, because they can maintain a sharp blade and can be used, without wearing out, many times [30].

Experimentally, a cylindrical-conical dental bur (see Figure 1) was used, of which the working active part was made of WC with the addition of Co, and the cutting blades were made of stainless steel. This dental bur was used for three months, in a dental surgery every day.

For surface analysis, an Olympus SZ61 stereo microscope and a Jeol JSM – 6610LV scanning microscope (USA) were used. In addition, the Jeol JSM – 6610LV scanning microscope working with an X-ray analyzer, Oxford EDS (England), was also used to analyze the chemical composition of both surfaces (initial and worn).

Depending on the movement of the processed material and the movement of the milling cutter, we distinguish the following machining methods (Figure 4): the method in which the feed rate is opposite to the milling cutter movement (against the feed, Figure 4a) and the method in which the two movements have the same direction (Figure 4b).



(a) (b)

Figure 4: Forces acting in the milling processing the opposite direction to the feed motion (a) and in the same direction as the feed motion (b)

The components, F_r and F_t, as radial and tangential forces of the resultant force, F, which represents the milling/cutting force, tend to lift or press the material to be processed on the machine table.

In the method where the feed speed is opposite to the milling motion, the blade attacks the material to be processed from the smallest chip thickness (Figure 4a), and in the milling method where the two movements have the same direction, the milling blade touches the material at the maximum chip thickness, which leads to the occurrence of shocks due to the radial component, F_r (Figure 4b).

An optimal cutting regime is obtained taking into account: the material to be processed, the type and material of the milling cutter, the quality and precision of the surface resulting from the milling process, and the technological system used.

Some theoretical aspects

The depth of cut (chip thickness), s represents the value of the size of the cutting surface in contact with the processed material in the perpendicular working plane, and the size of the line between the cutting edge of the active part and the processed material, at a complete rotation, measured in the perpendicular plane in the direction of advance, represents the length of the contact surface, *l*. The two sizes, *s* and *l,* measured in mm, must comply with the requirements imposed by the optimal regime in the working process.

To execute the milling process, the regime speed, *n*, is chosen, and the milling head with the cutting blades in its rotational movement cuts the chips from the material being processed at the established working depth, with each blade.

Depending on the direction of rotation of the dental milling head and the direction of rotation of the material being processed, the material chips can be cut in the direction of rotation or opposite to the direction of rotation. Thus, any point on the blades of the dental milling head describes in its movement a trochoid-shaped curve shown in figure 5 [31,32].

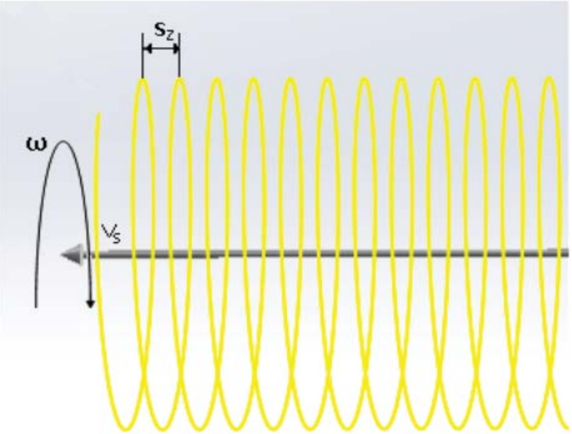


Figure 5: Trochoid curve described by a cutting blade on the dental bur head.

ω and v_s in Figure 5 are the angular velocity, respectively, the feed of the dental bur, given by the relations:

$$\omega = 2\pi n/60 \ (\mathrm{s}^{-1}), \qquad (1)$$

and

$$v_s = s_z \cdot z \cdot n \ (\mathrm{mm/rot}), \qquad (2)$$

where: s_z – feed per blade in mm; z – number of blades of the active part of the dental bur; n – speed of the dental bur in rpm.

Chip thickness, s_z (feed per blade) at the level of the processed material, cut by a blade, is determined by the relationship:

$$s_z = (2\pi \cdot v)/(n \cdot z) \ (\mathrm{mm/rot}), \qquad (3)$$

where: v – peripheral speed of the head (active part) of the dental bur, in m/s, and

$$v = \omega \cdot D_f/2 \ (\mathrm{mm/s}), \qquad (4)$$

with D_f – average outer diameter of the dental bur, in mm.

From the relationship (3), it follows that the engine speed, feed, and number of blades influence the chip thickness and the surface roughness.

The shape of the chip section, depending on the speed of the dental bur head, *n,* and the working feed, s_z is presented in figure 6.

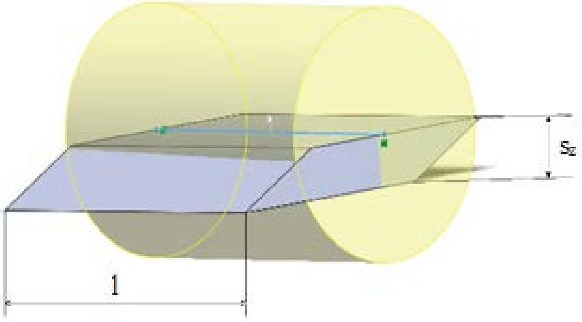


Figure 6: Shape of the chip section with dimensions s_z and *l*

Results and Discussion

Finite element analysis of the structure of dental burs

To have the certainty of confirming the metallographic and chemical analysis of the material structure of the studied dental bur, the author also proposed the analysis with the finite element method of the state of tensions and strains in the material structure of the type of dental bur investigated (WC – Co), respectively, the area/areas, where their values are maximum. The goal is to make the connection between the failure mode of the studied dental bur through wear and the state of tensions and strains in the structure of its material.

It is known that this method is a numerical method used to accurately determine the solutions to complex engineering problems and is considered to be one of the effective methods for solving many and varied practical problems [5].

The essence of the method is the discretization of a domain/region into subdomains/subregions (finite elements). This means replacing a domain/region with an infinite number of degrees of freedom with a system with a finite number of degrees of freedom. The elements are considered to be interconnected at specific points called "nodes" or nodal points. The shape, dimensions, number, and elements configuration are chosen so that the simulated domain/region is as close as possible to the original domain/region, with the greatest possible accuracy, without unduly increasing the computer effort to obtain the solution [33]. Figure 7 shows the general scheme for solving a problem using the finite element method.

The purpose of this study is to numerically simulate 3D with finite element the behavior of the structure of the dental bur under study, subjected to tensions (usually bending, torsion, compression, shear) that arise during operation, which

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is possible based on ref. [5]. First, the three-dimensional geometric model of the cylindrical-conical dental bur under study was created [35]. For 3D modeling, the parameterized Solid Works Premium design program was used, in the "Parts" module of the design program, in figure 8, different views and the Solid Works program interface are presented.

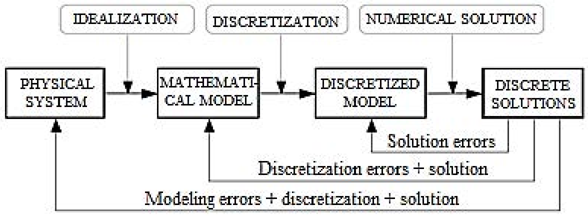


Figure 7: General scheme for solving a problem using the finite element method.

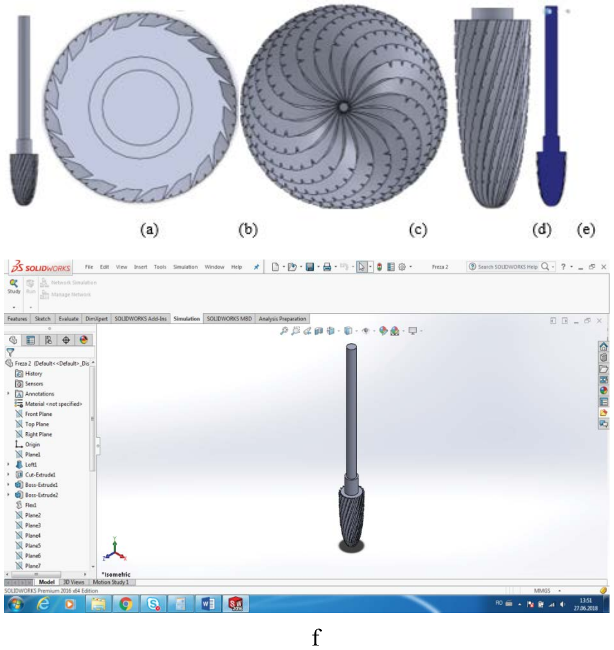


Figure 8: Positions of the dental bur: (a) front view; (b) top view; (c) bottom view; (d) detail on the milling area;(e) longitudinal section; (f) isometric view of the dental bur, as well as the interface of the software used.

The next stage consisted of introducing the 2D geometric model to the dental bur model in longitudinal section using the "Simulation" module of the Solid Works design program. In this regard, the following simplifications of the process were made:

- the analysis was performed in a plane state of deformation of the geometric model made for the cylindrical-conical dental bur model;

- the dental bur is considered embedded at the end of the foot area of the dental bur, where it receives movement from the pneumatically driven micromotor;

- on the outer area of the active part of the studied dental bur, it was considered that a pressure of 1MPa acts;

- the dental bur is driven in rotational motion with a speed of 30000 rpm (ω = 3141.6 rad/s).

Figure 9 shows the fatigue resistance curve of the dental bur material, and the axial (longitudinal) plane of the dental bur is shown in figure 10.

After the simulation, the program recorded the values of all the tensions acting on the geometrically modeled dental bur. In general, the tensions on dental burs are bending, torsion, compression, and shear.

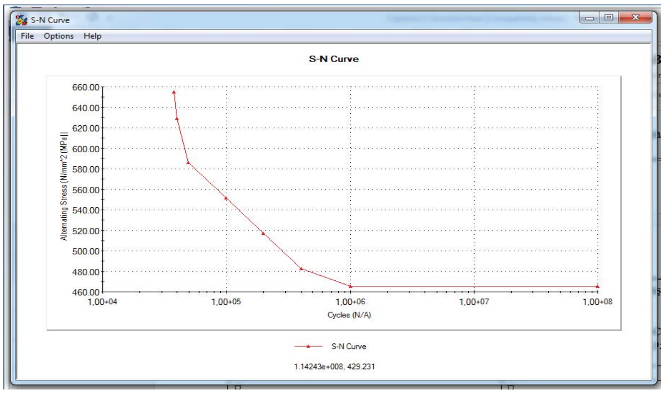


Figure 9: Fatigue curve of the alloy used to make the analyzed dental bur.

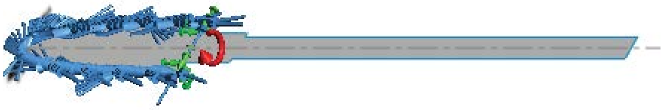


Figure 10: Axial (longitudinal) planes for the geometric model of the dental bur, after applying the simplifying assumptions.

The discretized finite element model of the dental bur is presented in figure 11.

Figure 11: Discretization of the geometric model with finite elements.

The results obtained for the type of dental bur analyzed, from the simulation in Solid Works, are presented below. Thus, figure 12 presents the values of displacements (position (a)), tensions (position (b)), and equivalent strains (position (c)) that occur in the dental bur during the stresses listed above (bending, torsion, compression, shear).

From the analysis of these data, it is observed that the node displacements, the largest from the bur structure, occur in the active cutting zone (the blades of the dental bur), with a maximum value of $5.75 \cdot 10^{-5}$ mm.

In figure 12(a), the equivalent tension values in the dental bur under the stress action are calculated according to the von Mises criterion.

Analyzing figure 12(b), it can be observed that in the structure of the dental burs a stress concentrator point appears, located in the milling zone, the values of the equivalent von Mises tensions created in this point being $6.995 \cdot 10^5$ Pa. Leaving aside this point, we observe that the maximum stress in the milling area of the dental bur is around $5.94 \cdot 10^4$ Pa. And, in figure 12(c) the values of the equivalent strains that occur in the dental bur under the action of the tensions are presented.

From the analysis of figure 12(c), it can be observed that the equivalent strain values occur in the dental bur as a result of the stresses to which it is subjected. Thus, the maximum equivalent deformation arises in the same stress concentrator point, with the maximum deformation value of $2.27 \cdot 10^{-6}$, while the minimum equivalent deformation has a value below $2.19 \cdot 10^{-9}$, for the dental bur.

Thus, by applying the finite element method, it was possible to determine the tensions and strains in the dental bur's material structure, establishing the critical points where they are maximum, to take the appropriate measures and intervene where and when it is necessary.

Evaluation of wear of dental burs

The dental burs from WC-Co, if used in contact with enamel, deteriorate prematurely. They work best with light pressure at high speed, which was demonstrated in ref. [26]. As mentioned above, the research was carried out in a dental clinic on commercial WC-Co dental burs of conical-cylindrical shape.

Surface analysis after three months of use was realized with the Olympus SZ61 stereo microscope and Jeol JSM – 6610LV scanning microscope (USA). In addition, the chemical composition analysis of both the initial and worn surfaces was performed with the Jeol JSM – 6610LV scanning microscope working with an X-ray analyzer, Oxford EDX (England).

Figure 13 shows the macroscopic image of the surface of the WC-Co dental bur, obtained with the help of the Olympus SZ61 stereo microscope. Figure 13(a) shows the dental bur in its initial/original form, and Figure 13(b) shows the conical head (the conical-cylindrical active part) of the bur, where abrasion wear of the edges of the dental bur head is observed.

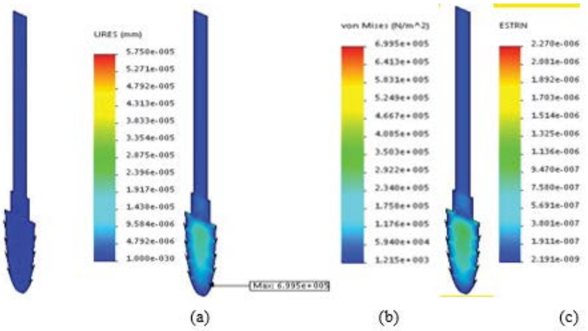
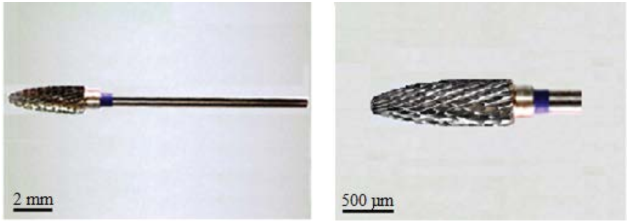


Figure 12: Displacement values in the geometric model (a), equivalent stress values according to the von Misses criterion (b), equivalent strain values of the dental bur.

To observe the surface of the dental bur from WC-Co, a scanning electron microscopic (SEM) analysis was performed [5,34]. Thus, wear marks were observed after three months of use on the tested dental bur. At the same time, WC-Co burs are also designed to mill more efficiently and reduce the risk of breaking or chipping.



(a) (b)

Figure 13: WC-Co dental bur: initial shape (before use) (a), dental bur head with worn cutting edges (after use) (b)

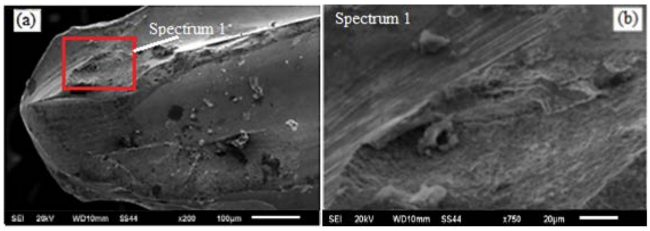
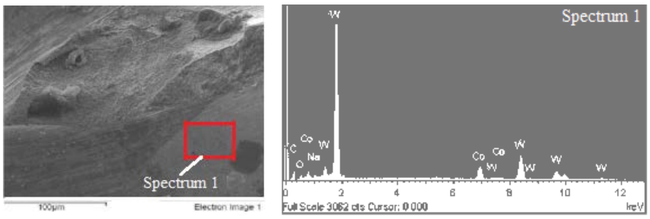


Figure 14: Wear of the active part of the dental bur from WC-Co: (a) after use (250X); (b) shape of the milling surface (750X).

As a result, the active part of the dental bur from WC-Co was degraded by abrasion, and on its surface, defects were observed in the form of crushes, breaks, cracks, and microcracks, as well as the deposition of tooth enamel dust (Figure 14(a)).

The material losses on the active surface of the dental bur (presence of craters) after three months of use are shown in figure 14(b), magnified by 750X.

Then, in figure 15, the chemical composition analysis of the initial surface (before use) of the active part of dental bur from WC–Co is presented, in a spectrum 1 (see the marked



(a) (b)

Figure 15: Analysis of the chemical composition of the initial surface of the WC–Co dental bur: before using, spectrum 1- marked area (a) and the histogram of the distribution of chemical elements (b)

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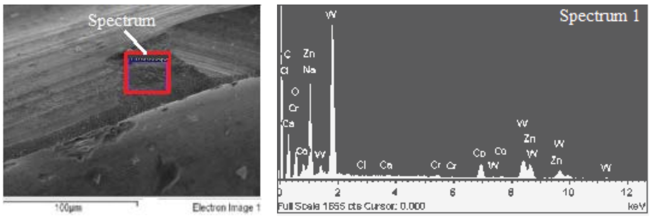
area in figure 15(a) (without being damaged), respectively, the histogram of the distribution of chemical elements, figure 15(b).

The results of the EDS analysis of the chemical composition of the surface of the WC–Co dental bur, without damage (see spectrum 1, Figure 15), are presented in table 1.

Table 1: Chemical composition of the initial active part surface (before using) of dental bur from WC–Co by EDS analysis.

Chemical element	Mass Spectrum 1 [%]
C	11.05
O	2.94
Na	0.32
Co	11.03
W	74,66



(a) (b)

Figure 16: Chemical composition analysis of the active part surface of the dental bur from WC–Co (spectrum 1), after use (a), and the histogram of the distribution of chemical elements (b)

Table 2: Chemical composition of the active part surface of the dental bur from WC–Co, after use.

Chemical element	Mass Spectrum 1 [%]
C	28.29
O	11.37
Na	1.71
Cl	0.18
Ca	0.22
Cr	0.39
Co	6.27
Zn	12.03
W	39.50

On the other hand, figure 16 presents the chemical composition analysis of the active part surface of the same dental bur, after use (see spectrum 1, figure 16(a) and the histogram of the distribution of chemical elements, figure 16(b)), and the results of the EDS analysis of the damaged surface (after use) of the dental bur of WC-Co are presented in table 2.

Therefore, the chemical composition EDS analysis of the dental bur from WC-Co pointed out new chemical elements after its use. These new elements come from the dental bur sterilization and the tooth tissues during the use of the bur.

Conclusions

The working process of dental burs is similar to the milling process, and removing dental material with their help is a complex phenomenon, similar to removing by friction and wear, or even materials-chipping by milling.

The main cause of dental burs damage/failure is worn in various ways, in a longer or shorter time, depending on the parameters of the work process, material hardness from which the dental burs are made, and the type of dental material processed.

Based on complex experimental observations and research, this phenomenon was analyzed and validated by the finite element method.

Chemical analysis of the material of the tested dental bur and the dental material processed during the experiments allowed determining the mechanical properties of the active part of the dental bur studied and solving some complex problems encountered in the dental field.

The finite element analysis pointed out that in the active area of the dental bur, tensions and strains are maximized. Therefore, the structure and chemical composition in this area must be conceived and realized practically and physically, to ensure the necessary parameters/characteristics/properties in the work process and their reliability and durability.

The spectrophotometric analysis with the X-ray analyzer (EDS), showed the presence of several chemical elements (W, Co, Cr, Zn, Cl, Ca, C, O, Na) in the material composition of the active part of the dental bur.

The wear behavior was analyzed by microscopic analysis and SEM of the surface of the active part of the dental bur, after the work process, depending on the speed, feed, and properties of the material of the dental bur, tested for a certain period of time.

The predominant parameter on the wear of the active part of the dental bur is the speed of the dental bur.

This proves that the loss of material by friction and the cutting milling (detachment/removal) of material at the contact of the dental bur - dental material, occurs over time, after covering an angular distance (circular friction length) in the work process, which has the effect of wear.

This leads to the establishment of criteria for improving the work regime, increasing their operating life, optimizing and improving the work regime, and possibly the materials from which they are constructed, respectively, for replacing worn dental burs.

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Conflicts of interest

The authors declare no conflicts of interest

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