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Analysis of the Failure Mode of Dental Burs Due to Tear and Wear

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Abstract

The topic of the paper falls within the new research directions regarding the wear of dental burs, addressing the concept of their durability and reliability. Considering the operating life of dental burs and the conditions imposed by the environment, a series of elements that underlie the occurrence of the wear phenomenon are highlighted. 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. The theoretical aspects, state of stresses and strains, their functional parameters in the work processes were identified, and one of the ways of evaluating the tear and wear of the active part of dental burs.

Keywords: dental bur; tear; wear; durability; reliability

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1. Introduction

Dental engineering is the field of development of industrial branches for the supply of dental medicine. The main task of this industry is the proper design and quality control of dental instruments. Quality, workmanship, safety of use for operators and patients, corrosion, mechanical resistance, are just a few characteristics that should be taken into account when designing dental devices 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.

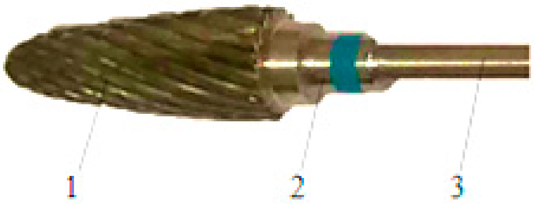


Figure 1. Components of a dental bur: the head (active part) -1, the neck - 2, and the foot of the bur - 3.

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).

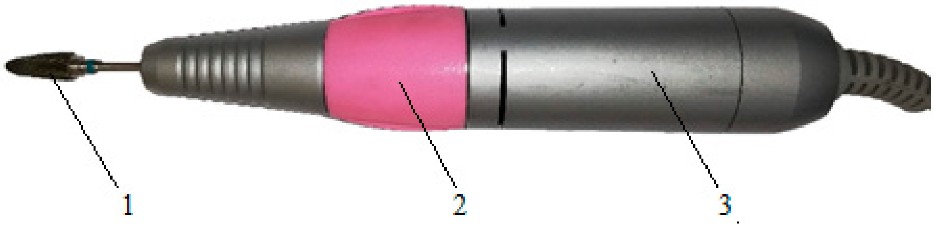


Figure 2. Micromotor equipped with a dental bur: 1 – dental bur; 2 – handle; 3 – electric micromotor.

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.

On the head of the dental bur, the cutting blades are made. The greater the 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 (Figure 3) [5,7]. However, those with a positive rake angle are mainly designed for chipping soft materials (e.g., acrylic materials) to remove material during cutting and prevent bending of the instrument. When the angle of inclination of a bur blade is too high, 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.

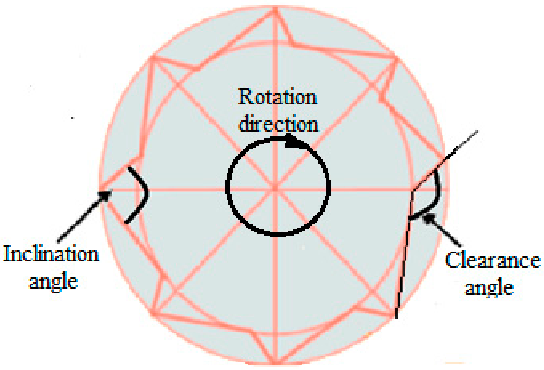


Figure 3. Schematic diagram of rake and clearance angles relative to the cutting direction.

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 [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.

2. 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 two most common materials used are stainless steel and WC [11–15]. Each material has its own specific advantages and disadvantages.

Carbon steel wears quickly and corrodes easily, and thus seems to be an unsuitable material choice for dental burs. However, at lower speeds, the wear rate associated with the cutting process is significantly reduced, and steel may be a suitable material [16]. The main corrosive environment experienced on dental burs has been during the sterilization process, but oral conditions also contribute to this [16].

Stainless steel provides a less effective cutting edge than carbon steel, but has a higher resistance to corrosion. Stainless steel is a relatively inexpensive material (compared to WC diamond materials, etc.), which makes it suitable for dental burs, provided that it is intended for single use and is classified as a disposable dental bur [13,17].

The high hardness makes WC extremely wear-resistant, but it is brittle compared to stainless steels [18]. This recommends that the blades on the active side of dental burs be made of WC, and the shank can be made of steel. Sintering is used to bond the carbide blades to the steel shaft. WC is also suitable for dental burs intended for use at lower speeds, when they are to be used several times [6,11]. Instruments made of WC are much more expensive than those made of steel, but compensate for this by increasing their service life [17,18].

Dental burs made of WC contain Cobalt as a binder in percentages of about 6%, which provides these instruments with additional hardness. Two parameters, namely the WC/Co ratio and its particle size (WC), control the basic properties of the material. In general, coarse-grained WC, combined with a high Co coefficient, provides increased shock and impact resistance [19,20]. However, finer-grained WC is harder and provides greater wear resistance.

Therefore, to achieve optimal performance, it is necessary to avoid premature damage in order to have higher durability [21,22]. The most common causes of damage to dental burs are operation, sterilization, and disinfection [23,24].

As previously specified, WC is an extremely hard and, at the same time, brittle material. The WC–Co composite is similar to ceramics, consisting of WC grains/granules that are mixed with Co. This material has very good mechanical and physical properties, namely: hardness, fracture resistance, high temperature resistance, high thermal conductivity, good electrical conductivity, and wear resistance [25–27].

Most WC dental materials 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% by weight of Co is added as a binder. Very important parameters are the WC/Co ratio and the size of the WC particles, on which the properties of the material depend.

To obtain a material with better shock resistance, or impact resistance, WC in the form of granules should be combined with a higher percentage weight of the Co binder. However, as far as materials with higher wear resistance are concerned, WC with 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.

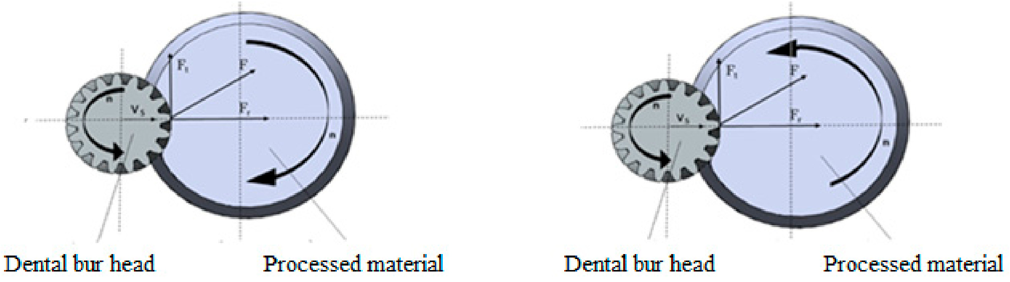
Dental WC-Co mixture burs are most commonly used for crown preparation and crown cutting, filling preparation, including removal of old fillings, root canal, root preparation and smoothing, caries removal, bone contouring, etc. [29] and are the subject of research in this paper.

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

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

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_t and F_r, as tangential and radial 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.

3. 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].

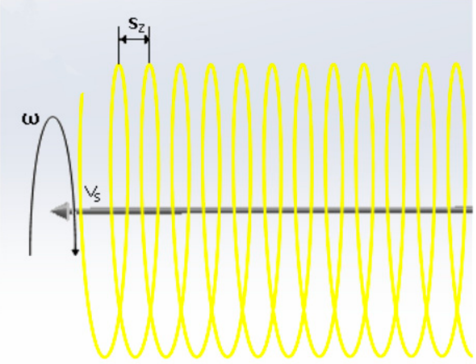


Figure 5. Trochoid curve described by a cutting blade on the dental bur head.

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

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

and

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

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

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

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

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

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.

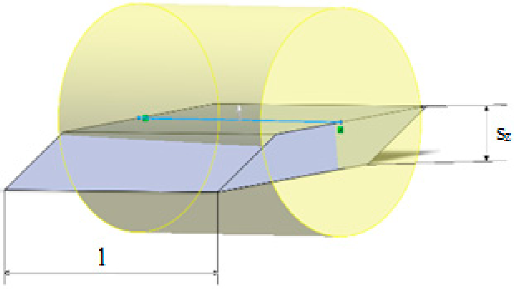


Figure 6. Shape of the chip section with dimensions s_z and l.

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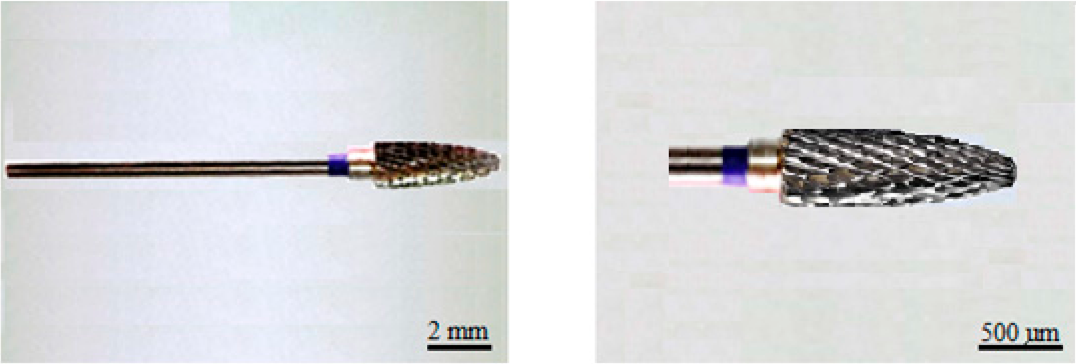
4. Results and Discussion

4.1. Evaluation of Wear of Dental Burs

WC-Co burs deteriorate prematurely if used in contact with enamel. They work best at high speed with light pressure, which was demonstrated in ref. [26]. 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 performed using an Olympus SZ61 stereo microscope and a Jeol JSM – 6610LV scanning microscope (USA). In addition, the chemical composition analysis of both the initial and worn surfaces was performed using a Jeol JSM – 6610LV scanning microscope working with an X-ray analyzer, Oxford EDX (England).

The macroscopic image of the surface of a WC-Co dental bur obtained with an Olympus SZ61 stereo microscope is shown in Figure 7. Figure 7(a) shows the dental bur in its initial/original form, and Figure 7(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.



(**a**) (**b**)

Figure 7. WC-Co dental bur: initial shape (before use) (a), dental bur head with worn cutting edges (after use) (b).

Scanning electron microscopic (SEM) analysis was performed to observe the surface of the WC-Co dental bur [5,33]. Thus, after three months of use, wear marks were observed on the tested bur. At the same time, WC-Co burs are designed to cut more efficiently and reduce the risk of chipping or breaking. As a result, the active part of the bur head was degraded by abrasion, and defects in the form of cracks, crushes, breaks, and microcracks were observed on the surface of the WC-Co dental bur, as well as the deposition of tooth enamel dust (Figure 8(a)).

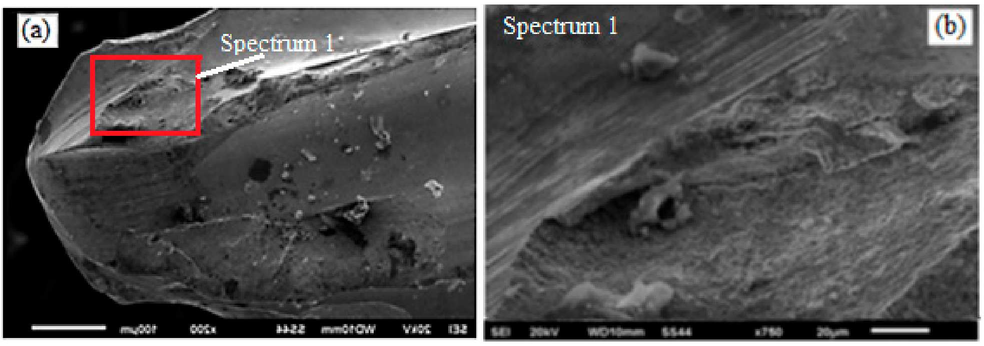
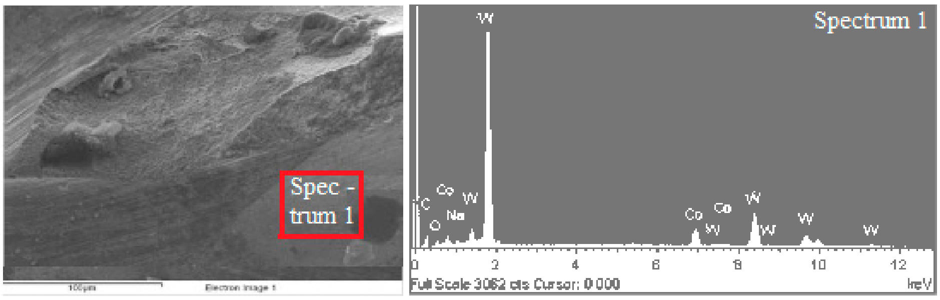


Figure 8. Wear of the WC-Co dental bur head: (a) after use (250X); (b) shape of the (active) cutting surface of the WC–Co dental bur (750X).

The material losses on the active surface of the dental bur (presence of craters) after three months of use are shown in Figure 8(b), magnified by 750X.

Then, in Figure 9, the analysis of the chemical composition of the initial surface (before use) of the WC–Co dental bur is presented, in a spectrum 1 (see the marked area in Figure 9(a) (without being damaged), respectively, the histogram of the distribution of chemical elements, Figure 9(b).



(**a**) (**b**)

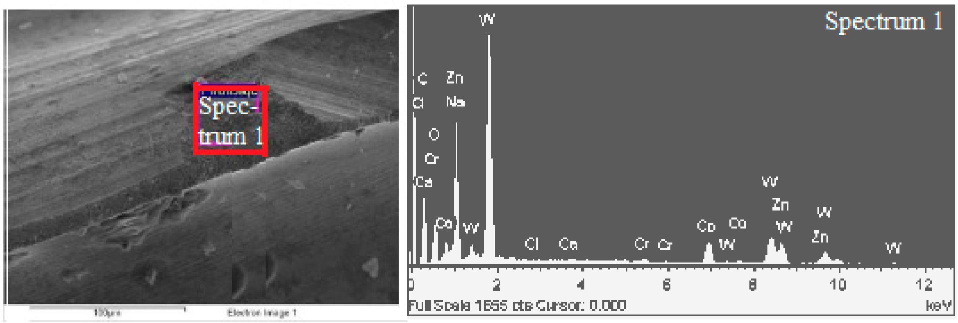
Figure 9. Analysis of the chemical composition of the initial surface of the WC–Co dental bur: before using, spectrum 1- marked area (a) and the histogram of the distribution of chemical elements (b).

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 9), are presented in Table 1.

Table 1. EDS analysis of the chemical composition of the initial surface (before using) of the WC–Co dental bur.

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

On the other hand, Figure 10 presents the analysis of the chemical composition of the surface of the same dental bur, after use (see spectrum 1, Figure 10(a) and the histogram of the distribution of chemical elements, Figure 10(b)), and the results of the EDS analysis of the chemical composition of the damaged surface (after use) of the WC-Co dental bur are presented in Table 2.



(a) (b)

Figure 10. Chemical composition analysis of the surface of the WC–Co dental bur (spectrum 1), after use (a) and a histogram of the distribution of chemical elements (b).

Table 2. EDS analysis of the chemical composition of the surface the WC–Co dental bur after use.

Chemical element	Mass Spectrum 1 [%]
C	28.29
O	11.37
Na	1.71

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Cl	0.18
Ca	0.22
Cr	0.39
Co	6.27
Zn	12.03
W	39.50

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

4.2. 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 stresses 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 stresses and strains in the structure of its material.

It is known that the finite element method is a numerical method that can be 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 finite element method is the discretization of a domain or region into subdomains or subregions (finite elements). This means replacing a domain 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 configuration of the elements are chosen so that the simulated domain is as close as possible to the original domain, with the greatest possible accuracy, without unduly increasing the computer effort to obtain the solution [34]. Figure 11 shows the general scheme for solving a problem using the finite element method.

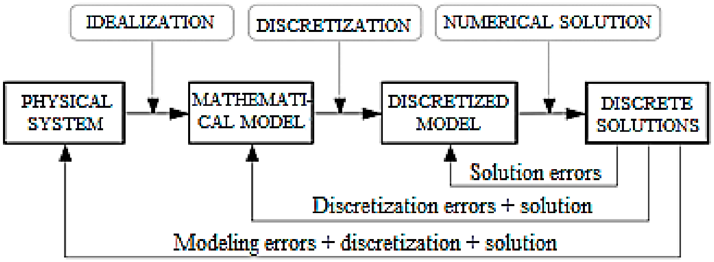


Figure 11. General scheme for solving a problem using the finite element method.

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 stresses (usually bending, torsion, compression, shear) that arise during operation, which 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 12, different views and the Solid Works program interface are presented.

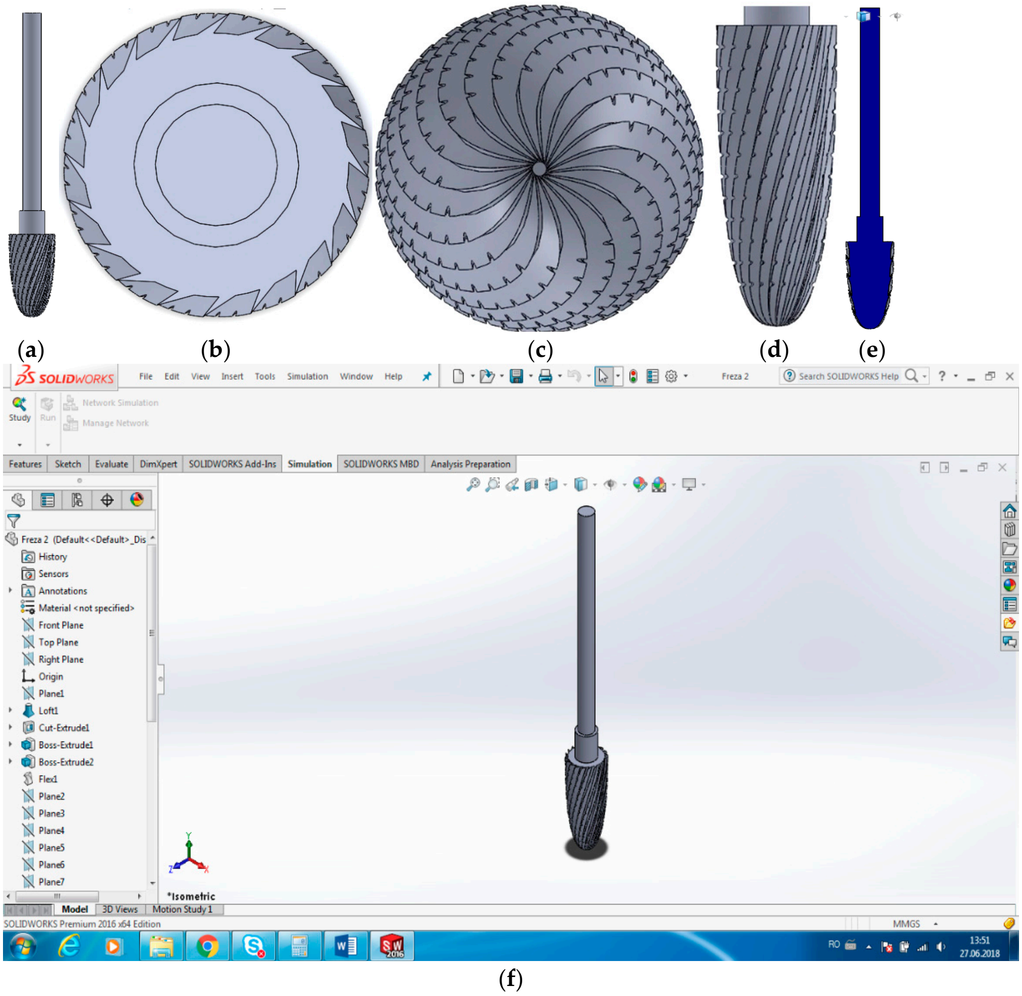


Figure 12. Positions of the dental bur: (a) front view; (b) top view; (c) bottom view; (d) detail on the milling area;(e) longitudinal section; (f) isometric view of the dental bur, as well as the interface of the software used.

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 in 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 ($\omega = 3141.6$ rad/s).

Figure 13 shows the fatigue resistance curve of the dental bur material, and the axial (longitudinal) plane of the dental bur is shown in Figure 14.

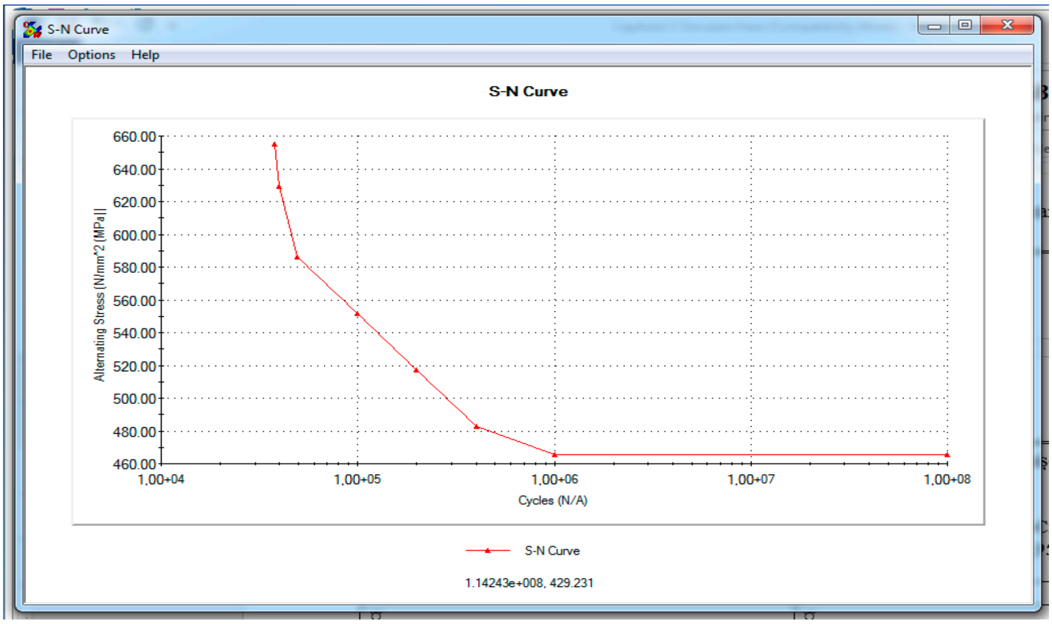


Figure 13. Fatigue curve of the alloy used to make the analyzed dental burs.

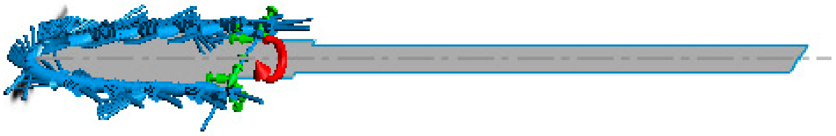


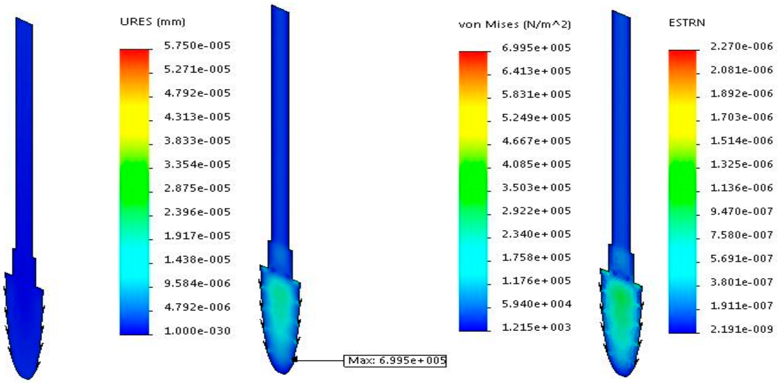
Figure 14. Axial (longitudinal) plane for the geometric model of the dental bur, after applying the simplifying assumptions.

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

The discretized finite element model of the dental bur is presented in Figure 15.

Figure 15. Finite element discretization of the geometric model.

For the type of dental bur analyzed, the results obtained from the Solid Works simulation are presented below. Thus, Figure 16 presents the values of displacements (position (a)), stresses (position (b)), and equivalent deformations (position (c)) that occur in the dental bur during the stresses listed above (bending, torsion, compression, shear).



(**a**) (**b**) (**c**)

Figure 16. Displacement values in the geometric model (a), equivalent stress values according to the von Mises criterion (b), equivalent strain values of the dental bur.

From the analysis of these data, we observe that the displacements of the nodes in the bur structure, the largest, 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 16(b) are presented the equivalent stress values in the dental bur under the action of the stresses, stresses calculated according to the von Mises criterion.

Analyzing Figure 16(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 stresses 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 16(c) the values of the equivalent deformations that occur in the dental bur under the action of the stresses are presented.

From the analysis of Figure 16(c), we can observe the values of the equivalent deformations that occur in the dental bur following the stresses to which it is subjected. Thus, the maximum equivalent deformation arises in the same stress concentrator point, the value of the deformation being $2.27 \cdot 10^{-6}$, while the minimum equivalent deformation for the dental bur has a value below $2.19 \cdot 10^{-9}$.

Therefore, by applying the finite element method, it was possible to determine the stresses and deformations in the structure of the dental bur’s material, establishing the critical points where they are maximum, to take the appropriate measures and intervene where and when necessary (it is necessary).

5. Conclusions

Dental engineering represents the field of development of industrial branches for the supply of materials necessary for the medical field, in general, and dentistry in particular. The main task of this industry is to obtain an adequate design and quality control of dental instruments. Quality, workmanship, safety of use for operators and patients, corrosion resistance, are just a few characteristics that should be taken into account when designing dental devices and drills.

The shape of the active part of dental drills depends on the purpose pursued in dental work processes. The working process of dental drills is assimilated to the milling process by chipping, and the process of removing dental material with the help of dental drills is a complex phenomenon, similar to friction and wear, or even chipping of materials.

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

The analysis of this phenomenon was carried out experimentally and validated by the finite element method based on complex observations and research.

Some complex problems encountered in the dental field were solved by chemical analysis of the material of the tested dental burs and the dental material processed during the experiments, respectively, determining the mechanical properties of the active part of the dental burs studied.

The finite element analysis showed that stresses and deformations are maximum in the active area of the dental burs. Therefore, it must be taken into account that the structure and chemical composition in this area should be designed and realized practically and physically, in order to ensure the properties/characteristics necessary in the work process, so that their durability and reliability are ensured.

From the spectrophotometric analysis with the X-ray analyzer (EDS), the presence of a large number of chemical elements (W, Co, Cr, Zn, Cl, Ca, C, O, Na) in the composition of the material of the dental bur was investigated.

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

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

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

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