"POLITEHNICA" UNIVERSITY OF BUCHAREST

FACULTY OF BIOTECHNICAL SYSTEMS ENGINEERING

MECHANICAL ENGINEERING

REZUMAT TEZĂ DE DOCTORAT
ABSTRACT OF PhD THESIS

Studii and cercetări privind durabilitatea and fiabilitatea frezelor stomatologice

Studies and research on the durability and reliability of dental milling cutters

Scientific leader:

Prof. dr. ing. Filip Ilie

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DOCTORAL CO*MM*ISSION

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Bucharest, 2021

Rezumat

Teza de doctorat îand propune să aducă o contribuție modestă la stabilirea durabilității and fiabilității frezelor stomatologice ținând cont de: tipul materialului din partea activă a frezei, parametrii procesului de lucru respectiv turația acesteia, parametrii constructivi ai părții active respectiv forma and unghiurile lamelelor tăietoare, timpul de lucru and materialul prelucrat.

Teza este structurată în 6 capitole în care se găsesc tabele cu datele achiziționate, grafice, figuri and fotografii din timpul cercetărilor. De asemenea teza este însoțită de referințe bibliografice and anexe care cuprind tabele din literatura de specialitate and rezultatele analizei cu element finit. După stabilirea obiectivelor and aplicarea metodologiei de cercetare experimentală prezentată în teză, în urma studiilor and cercetărilor au rezultat următoarele:

Estimarea duratei de viață a frezei stomatologice, la cele patru turații and cinci timpi, folosite în testele experimentale and prin modelare statistico-matematică a rezultatelor experimentale s-au confirmat datele din literatura de specialitate că viteza frezei (de așchiere) este factorul determinant principal al duratei de viață a sculei.

Prin dezolarea modelul matematic "pradă-prădător" pentru estimarea uzurii and a durabilității parții active a frezelor s-a putut observa că materialul, configurația and compoziția materialului frezei îi permite acesteia să fie eficientă, ceea ce înseamnă că o cantitate mică de material al frezei stomatologice pierdută, elimină mai mult material din materialul dentar frezat.

Cu ajutorul funcției de risc instantaneu se observa că timp de 11 ore riscul instantaneu de defectare este sub 10% în a 12-a ora de funcționare riscul de defectare crește aproximativ exponențial.

S-a stabilit că frezele stomatologice, mai precis partea activă de frezare a acestora este un element fără restabilire automată (nereparabil).

Abstract

The doctoral thesis aims to make a modest contribution to establishing the durability and reliability of dental cutters taking into account: the type of material in the active part of the cutter, the parameters of the work process and its speed, the constructive parameters of the active part and the shape and angles of the cutting blades, work time and processed material.

The thesis is structured in 6 chapters in which there are tables with the acquired data, graphs, figures and photos during the research. The thesis is also accompanied by bibliographic references and annexes that include tables from the literature and the results of the finite element analysis. After establishing the objectives and applying the experimental research methodology presented in the thesis, the studies and research resulted in the following:

The life of the dental cutter was estimated at the four speeds and five times used in the experimental tests and by statistical-mathematical modeling of the experimental results the data from the literature were confirmed that the cutting speed is the main determining factor of the tool life.

By desolating the mathematical model "prey-predator" to estimate the wear and durability of the active part of the cutters it was observed that the material, configuration and composition of the dental cutter material allows it to be efficient, which means that a small amount of material of the dental cutter lost , removes more material from the milled dental material

With the help of the instantaneous risk function it is observed that for 11 hours the instantaneous risk of failure is below 10% in the 12th hour of operation, the risk of failure increases approximately exponentially. It has been established that dental cutters, more precisely their active part, is an element without automatic (irreparable) restoration

Cuvinte cheie:Freză stomatologică, durabilitate, fiabilitate, model statistico-matematic, uzură

Keywords: Dental milling cutter, durability, reliability, statistical-mathematical model, wear

CONTENT

FOREWORD

The research and development of optimizing the durability and reliability of dental cutters was the main direction and motivation for the realization and completion of the doctoral thesis.

The doctoral research activity consisted of stages regarding the choice of the doctoral topic, establishing the objectives for the topic, the in-depth study of the literature, establishing and developing the experimental program, making the stand for experimental tests, acquisition and processing of experimental data, supporting progress reports. dissemination of results through the publication of scientific articles in specialized journals and national and international scientific conferences, symposia and congresses and ended with the elaboration of documents necessary for the public defense of the doctoral thesis.

The thesis is structured in 6 chapters, as follows:

Chapter 1 of the paper, includes a review of the current state of research and achievements on dental cutters nationally and internationally and how to identify their types. The theoretical aspects and their functional parameters in the work processes were identified and one of the ways to assess the wear of the active part used internationally was presented.

Chapter 2 refers to the main elements regarding the theoretical aspects of the friction-wear process. In the first part of the chapter the notion of tribosystem was described, notions regarding the friction of surfaces, and in the second part of the chapter being presented the types of wear, the formation of the wear particle and elements of the statistical calculation of wear.

Chapter 3, the first part describes the metallographic and chemical analysis of dental cutter materials by analysis using X-ray fluorescence spectrometer (XRF), analysis using the finite element method, determining the mechanical properties of the active part of dental cutters, and performing a test stand.

The second part of the chapter presented the research program, the initial measurements and the work processes within the research program on the mass of the tooth cutters and the angles of the active part. Also in this part were analyzed the experimental results on the wear of the characteristics presented above by statistical-mathematical modeling of the wear phenomenon in dental cutters based on experimental results (interpolations, functions, optimal points) establishing that the predominant parameter on the wear of the active part of dental cutters is represented by the speed of the dental cutter.

Chapter 4 presents the research conducted by the author on the durability and reliability of dental cutters.

It was established that the dental milling cutters, more precisely the active part of their milling is an element without automatic restoration (irreparable), after the occurrence of the defect or loss of working capacity.

The life of the dental cutter was estimated at the four speeds and five times used in the experimental tests and the data from the literature were confirmed that the cutting speed is the main determining factor of the tool life.

The mathematical model "prey-predator" expressed in a system of first-order differential equations by AJ Lotka and V. Volter was developed to estimate the wear and durability of the active part of the tooth cutters where it could be seen that the material, configuration and composition of the material The cutter allows it to be efficient, which means that a small amount of lost dental cutter material removes more material from the milled dental material.

With the help of the instantaneous risk function it is observed that for 11 hours the instantaneous risk of failure is below 10%, and in the 12th hour of operation the risk of failure (which in the case of the active part of the dental cutter means decommissioning) increases approximately exponentially, ie after 11 hours of operation it is normal to replace the dental cutter.

According to the experimental research, the researched dental cutters can operate without major risk of failure up to 10 hours, which is very close to those calculated analytically based on experimental results, which confirms the veracity of experimental results and the correlation between analytical calculation and test experimental results. Also, the experimental results of the mass lost by wear on the active part of the dental cutters have a normal distribution and the probability density is a function of normal distribution or Gaussian distribution.

Chapter 5, includes aspects related to the durability and reliability of dental cutters. In this chapter the author estimates the life of the active part of the dental cutter, in relation to the sharpening angle, the estimation of wear and durability of the active part of the dental cutters, shows the effect of of the constructive working parameters of the dental milling cutters on the dental materials subjected to processing, presents the influence of the concentration of chemical elements on the material properties of the active part of the dental milling machine. reliability for the active part (samples) of dental cutters and calculates the characteristic sizes of the reliability of dental cutters.

Chapter 6 presents the general conclusions of the paper, the original contributions of the thesis, according to the proposed objectives, the presentation of how to capitalize on the results obtained in the field studied and future research directions.

This paper was developed under the scientific guidance of Mr. Professor Dr. Filip Ilie to whom I thank for his commitment, for the guidance and specialized advice he gave me throughout the study and research, for the preparation and completion of the thesis. Through his communication and discussion skills, through the suggestions and comments made, he made a special contribution to the success of this doctoral thesis.

I would also like to thank prof. Univ. Dr. Eng. Voicu Gherghe, Prof. Univ. dr. eng. Biriș Sorin-Ștefan, prof. univ. Dr. Eng. Ladislau David, Prof. Univ. dr. eng. Căsăndroiu Tudor, univ. prof. dr. eng. Antoniac Vasile Iulian, prof. univ. Dr. Eng. Maican Edmond, Associate Professor dr. eng. Ipate George from the POLITEHNICA University of Bucharest for the guidelines, comments and specialized proposals during the scientific evaluations at exams, progress reports and from the preliminary defense of the thesis.

I also express my sincere gratitude to the entire team of organization and management of POLITEHNICA University of Bucharest.

Last but not least, I would like to thank my family for their understanding during the work and for the moral support provided during the difficult times.

I emphasize the fact that I completed this doctoral thesis through my direct analysis and research activity, based on reference scientific resources, modern laboratory equipment, within the doctoral school "Biotechnical Systems Engineering".

CHAPTER I
THE IMPORTANCE OF THE TOPIC. OBJECTIVES OF THE DOCTORAL THESIS

1.2 The objectives of the doctoral thesis

The general objective of the doctoral thesis is the study and research of the durability and reliability of dental (dental) cutters. The study of the literature on the current state of research and achievements at international and national level on the durability and reliability of dental cutters, given the complexity of their work processes required the approach of studies and research based on the following strategies:

a) Documentation on the current state of research and achievements at national and international level on the durability and reliability of dental cutters;

b) Theoretical study on the friction-wear process, by:
- notions about friction and wear of surfaces;
- elements justifying the statistical calculation of wear.

c) Solving complex problems encountered in the medical field of dentistry before the operation of dental cutters, by:
- metallographic and chemical analysis of dental cutter materials;
- determination of the mechanical properties of the active part of the dental cutters;
- analysis of the material structure of dental cutters using the finite element method.

d) Establishing the types of dental materials to be processed with dental cutters during experiments, by:
- determination of chemical composition;
- determination of mechanical properties;
- determination of the initial mass;

e) Realization of a stand in order to carry out the experimental researches, for:
- determination of the functional parameters of the dental cutters used in the experimental determinations;
- realization and adaptation of tests, for tests and experimental determinations;
- elaboration of the testing, experimentation and research methodology;

f) Establishing the wear behavior of the active part of the dental cutters (dental), in the working process (operation), by:
- determination of the initial mass of the dental cutters studied and their mass after certain work periods;
- establishing the degree of wear depending on the working time, speed, advance and the properties of the materials of the tested dental cutters;

g) Statistical-mathematical modeling based on the experimental results of the working process of the dental cutters, by:
- setting the recognition sizes (input and output parameters);
- establishing the optimal operating conditions (with friction and wear, minimum) in order to make the right choice of dental materials and dental cutters;

h) Correlation of the results obtained analytically (by modeling) with those obtained in experimental tests by:
- comparing the results obtained analytically by modeling, with those obtained experimentally;
- establishing the durability and reliability of dental cutters.

CHAPTER II
CURRENT STATE OF NATIONAL AND INTERNATIONAL RESEARCH AND ACHIEVEMENTS REGARDING THE RELIABILITY OF DENTAL CUTTERS

2.2. Identification of dental cutters

After studying the specialized literature on national and international achievements, the following conclusions were drawn:

All dental instruments are manufactured in accordance with EN ISO-Standard 6360. To achieve compliance, the International Organization for Standardization (ISO) has defined a standard description of rotary instruments used in dental technology. Each instrument is encoded with a separate ISO code number. This code consists of 15 numbers that are arranged in groups and simultaneously contain the description of the instrument

The main task of this industry is proper design and quality control of dental instruments. Quality, workmanship, safety of use for operators and patients, corrosion resistance, are just a few features that should be considered when designing dental appliances and cutters.

2.2.1 Constructive description of dental cutters

The shape of the active part of the dental cutters defines the types or variants existing and used in all dental work processes, depending on the purpose pursued.

At the base of all these variants are five classic shapes, namely: spherical, cylindrical, conical, cylindrical with rounded head, con-inverse. All other shapes are the result of changes in these five shapes, changes that take into account the length of the body of the dental cutter, rounding the terminal edges of the active part of the dental cutter.

2.5. Theoretical aspects regarding the work process and parameters

The working process of dental milling cutters is assimilated with the milling process by cutting. The main cause of decommissioning of dental cutters is wear in different ways, in a longer or shorter time, depending on the hardness of the material from which the dental cutters are made, the type of dental material processed and the parameters of the work process.

CHAPTER III
THEORETICAL ASPECTS REGARDING THE FRICTION-WEAR PROCESS

3.1 The friction-wear process. Elements for statistical calculation of wear

In this chapter are presented theoretical aspects regarding the wear milling process.

Starting from the notion of tribosystem (a tribological system consisting of at least two bodies in contact, including the environment in which their interaction takes place, with all relevant factors governing the tribological behavior of the system) is related to the process of friction-wear-lubrication (tribological process) of a technical system (friction coupling), a process that accompanies the friction of bodies in contact, having the effect of wear. The description of a tribosystem is based on a detailed assessment of the relevant inputs, outputs and losses of the system, as well as a general description of the structure of the system.

3.1.2 Notions of surface friction

Friction is defined as a complex phenomenon of mechanical, energetic and molecular nature, which takes place between the contact surfaces that have relative motion [30, 32]. On the other hand, friction is that phenomenon*n /* process that opposes a solid body in relative motion to another, and the force that arises (resistant) is opposite to the movement and refers to the effects it produces and can be perceived:

a) in the form of forces (friction forces, Ff), which act on the bodies that come in contact during a linear motion;

b) in the form of moments (friction moments, Mf), which act on the bodies that come in contact during the rotational movement;

c) as a process during which the mechanical work (mechanical friction work, Lmf or friction energy, Wf) is transformed into other forms of energy (heat, deformation energy, etc.).

For the study of friction are presented the concepts, theories and laws of different types of friction (dry, limit, mixed (semi-fluid), fluid, stick-slip (glue-slip)).

The study and deepening of the complex processes in the area of the contact surfaces of the bodies, allowed the issuance of several theories to lay the scientific foundations, after which the friction phenomena take place, namely:

- the mechanical theory was advanced as the deformable solid body was known
- the theory of molecular adhesion explains that the friction process is the result of overcoming the forces of molecular interaction that arise at the level of contact surfaces of bodies.
- the theory of welding bridges or the theory of Bowden and Tabor, whereby the frictional force is due to the force necessary to shear the welding bridges formed as a result mainly of molecular interactions at high temperatures, forming inter-metallic compounds
- the theory of elastic and plastic deformations, explains the friction as the energy spent for the elastic, elasto-plastic and plastic deformation of the asperities
- molecular-mechanical theory. This theory was issued by Coulomb who considered friction as a result of both overcoming the interaction forces between surfaces and climbing small roughnesses.
- the energy-quantum theory of friction-wear, assumes that the energy, through energy quanta, passes from one surface to another in the friction process, having as effect the transfer of material, respectively wear particles
- electrostatic friction theory, which suggests the transfer of electrons between friction surfaces, creating and maintaining a difference in electric potential

Regarding wear, it leads to the change of the initial state of the surfaces of a tribositem, as a result of the detachment of material, being therefore an undesirable phenomenon, having as effect the wear.

3.2 Notions of surface wear

Wear represents the effects of wear: traces of surface damage (in various ways) and products detached from surfaces. Wear depending on the mode and size of the measurement can be:

• linear;
• gravimetric or mass
• volumetric

Wear is characterized by a series of empirically established parameters, so not by logical theoretical relations, valid only under certain limit conditions, even if they are defined relatively logically. As seen above, depending on the mode and size of wear measurement we distinguish: linear wear, Uh, volumetric wear, Uv, gravimetric wear, Ug, which for the wear process are also considered parameters. If the causes leading to wear are taken into account, other parameters of the wear process are defined, namely:

- wear speed,
- wear intensity
- specific wear,
- relative wear,
- wear coefficient,
- wear resistance

By exemplifying the types of wear, you can specify:

- Adhesion wear
- Abrasive wear
- Fatigue wear
- Corrosion wear

The processes that take place by friction on the contact surfaces and in the surface layers, so in the microvolumes of the roughness in contact are of different nature and depend on a series of mechanical, physical, chemical, geometric and metallurgical factors.

Friction is a complex phenomenon characterized by energy consumption and material loss (wear) and is explained by the action of several components whose weights depend on the concrete elements of moving bodies with friction (surface topography, physical and mechanical properties of materials, speed, the environment between the contact surfaces, the rigid, elastic or plastic behavior of the contact materials, the presence on the friction surfaces of impurities, lubricant, etc.), in which the dominant mechanical and molecular components are dominant.

The coefficient of friction varies with the applied load (pressure) and the sliding speed and differs from the nature of the materials in the friction process, the nature and condition of the surfaces (physico-chemical state of the surface layers, state of microgeometry, etc.).

Wearing leads to the change of the initial state of the surfaces of a tribositem, by detachment of the material, the deterioration of the surfaces, an undesirable phenomenon, having as effect the wear.

Upon contact of two solids, on the contact surface, the asperities deform elastically, plastically or break by bending or shearing, which causes the friction-wear process to condition, but also to be conditioned by the friction surface, with effects not only to the surface, but also to a certain depth of the material.

The material particle detaches after exceeding a certain stored energy, of mechanical and adhesive nature, which acts on the friction surface and when the surface energy is exceeded by the elastic deformation energy.

The amount of material removed by wear can be determined both analytically and experimentally using indicators (wear rate or wear intensity), depending on the type of material (ductile, brittle, so hardness and toughness at break), the shape of abrasive particles , pressure in the contact area, friction coefficient, melting temperature, respectively atomic volume, etc.

3.3 Supporting elements for the statistical calculation of wear

The statistical calculation of wear is justified, even from the statistical nature of the friction-lubrication-wear process, because the analytical calculation relations (regression relations) start from the real situation reflected by experimental data, which take into account the interaction of all influencing factors.

In order to quantitatively extract the desired information, it is necessary for the phenomenon (process) studied to be able to find a model (statistical-mathematical) that incorporates as realistically as possible its essential characteristics and at the same time is not too complicated for analytical handling.

CHAPTER IV
EXPERIMENTAL RESEARCH REGARDING THE WORKING PROCESS OF DENTAL CUTTERS, THROUGH STATISTICAL-MATHEMATICAL MODELING

4.2 Development of research methodology through modeling and experimentation

The experimental analysis of a phenomenon must be validated by mathematical modeling, regardless of whether the mathematical model of the phenomenon is theoretical, empirical or mixed (theoretical-empirical). Theoretical-empirical or empirical models require extensive experiences to establish the relationships between input parameters and output parameters and control parameters of the modeled process. Once these models are established, validation is usually done on another set of experiments.

The phenomenon of removing dental material with the help of dental cutters is a complex phenomenon, similar to rubbing and wearing materials, or even cutting materials.

All these phenomena are mathematically modeled starting from experimental results obtained in complex and very expensive research. The large number of experimental data and parameters involved in the process, directly influences the accuracy and stability of the model. Statistical-mathematical models are now part of the statistical analysis of experimental data, so these models are briefly described in this chapter.

Important advances have been made in the mathematical modeling of the phenomenon of wear of a system in different phases of life, starting from the process of cutting metals. [8, 9, 32]. The dental milling process is very similar to a fine process of cutting milling.

In the literature are presented five mathematical models for the phenomenon of wear of the active flanks of metalworking tools, namely: the abrasive model for low-carbon steels coated with carbide; diffuser model for HSS material C-45 (high speed steel C-45); the model of the Taylor equation modified for tool life, the adhesive-diffusive model for low-concentration carbide-coated alloy steels and the deterministic model, differential for the working process of dental cutters.

Complex experimental studies on dental cutters are still being carried out through advanced research. Interesting experimental results regarding the working process of dental cutters are presented in ref. [4]. Here, the contact pressure values are given from the contact areas between the cutting tool and the material, related to their wear, even if not necessarily on the active area of a dental cutter.

A systemic image of the working process of the dental cutters helps to inventory the process parameters, as a result of the control of this process.

The input parameters of the process are:

- the parameters of the material from which the active part of the dental cutter (dental) is built: hardness. plasticization limit stresses (if any), breaking, thermomechanical characteristics. chemical composition, parameters that define the geometry of the cutting edges of the active part of the cutter;
- parameters of the material to be milled: hardness, breaking stresses, chemical composition and other thermomechanical characteristics;
- operating regime parameters (control parameters): rotational speed of the dental milling cutter, the pressing force of the milling cutter on the milled material; contact time; temperature;
- parameters of the working process: the limit quantity of the mass lost by the active part of the dental cutter in operation, or the life cycle of the cutter.

The working process of dental cutters being a complex one, many of the basic parameters of the process could be established and quantified only after the mathematical modeling of the phenomenon.

The results of complex experimental research on the working process of dental cutters are analyzed, by modeling due to the large number of experimental data and parameters involved in the process. The complexity of the work process in the dental medical field, as well as the parameters and factors that act on the process, imposed the approach of experimental research by integrating interdisciplinary fields.

4.3.1 Metallographic and chemical analysis of the dental cutter. Experimental studies and research

For the elaboration of the research methodology through modeling and experimentation, the proposed objectives were taken into account, the type of dental cutters, which were studied and the dental materials chosen for the experimental tests.

According to STAS 4203-74, the analysis of macro-microscopic metallographic samples consists in 4 stages:- prelevarea probelor;
- sanding of samples;
- polishing the samples;
- metallographic attack.

Given the fact that the nature of the material was not known. Nital 2% was attacked. The microstructures of Fig. 4.19 - the sample from F1 and fig. 4.20 - sample from F2 (magnification scale 500x).

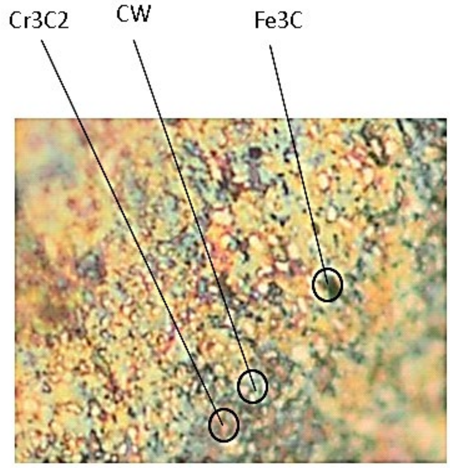


Fig. 4.19 F1 sample microstructure (500X)

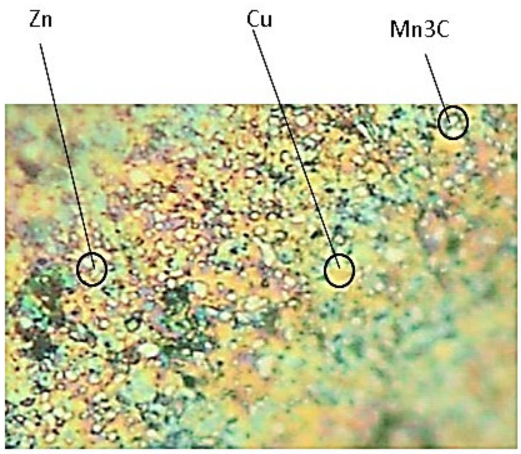


Fig. 4.20 F2 sample microstructure (500X)

4.4 Determination of hardness of tooth cutters by Vickers method

To measure the hardness of Vickers, an Innovatest type device (Ireland) was used, metrologically verified in 2018. 3 measurements were made on both test tooth cutters in two areas: in the middle of the cross section and at its edge, very close to the cutting edge. of the milling cutter. The values in table 4.1 were obtained. The pressing force was 5 N and the holding time of the penetrator was 10 seconds.

Table 4.1

Vickers hardness and tensile strength for compression stress

Measuring area	HV	Average HV	R_m (MPa)	Average R_m (MPa)
Middle	292.3	291.96	939.2	937.7
	293.4		943.4	
	290.2		930.5	
Margin	378.8	375.9	1216.4	1207.73
	370.5		1191.6	
	378.4		1215.2	

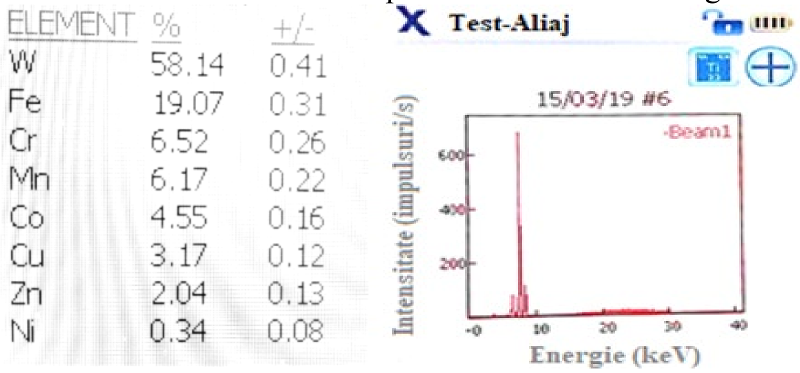
4.5 Finite element analysis of the structure of dental cutters

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

4.6 Determination of the chemical composition of the active part of the studied dental cutter

A Delta X-ray Fluorescence (XRF) spectrometer (Olympus NTD Inc. USA) was used for the chemical analysis of the active part of the dental cutter under study. which is a portable energy dispersion spectrometer. The XRF spectrometer determines the elemental composition of a material, identifies the component elements of a substance and quantifies the amount of elements present. An element is defined by the characteristic wavelength of the emitted X-rays (A), or of energy (E). The amount of element present in the substance is determined by measuring the intensity of the characteristic diffraction line.

In the analysis of portable X-ray fluorescence, the elements Lights Elements (LE, light elements) are considered those with atomic number less than 18 (Argon) and refer to the group Mg, Al, Si, P, S, Cl. The chemical composition using XRF and the energy spectrum of the X-ray fluorescence used to determine the composition can be seen in fig. 4.38.



ELEMENT	%	+/-
W	58.14	0.41
Fe	19.07	0.31
Cr	6.52	0.26
Mn	6.17	0.22
Co	4.55	0.16
Cu	3.17	0.12
Zn	2.04	0.13
Ni	0.34	0.08

a) b)

Fig. 4.38 Chemical composition (a) using XRF and X-ray fluorescence energy spectrum used to determine the composition (b)

4.7 Research method used. Construction of the test stand

In order to carry out the experimental researches within the thesis, an experimental stand was designed and built, having the composition presented in fig. 4.39. The operation of the stand is considered simple and is described below.

The stand consists of a support table (9) on which were placed two movable supports (3) one for the drive micromotor (5) of the dental cutter and another for the mandrel micromotor (8) for gripping and operating the material milled.

On the same support table were placed a dynamometer (1) for measuring the pressing force between the dental cutter and the milling material, a tachometer (2) for measuring and reading the speed of the dental cutter and the milling material, a variator (6) for determining the speed of the dental cutter and its variation, a micrometer 0 - 25 *mm* (7) for moving the chuck with the milling material, a plate (10) for determining the pressing force between the active part of the dental cutter and the milling material and two springs (5) to maintain the balance between the movement of the mandrel with the micrometric screw driven by the plate with the weights established for the pressing force.

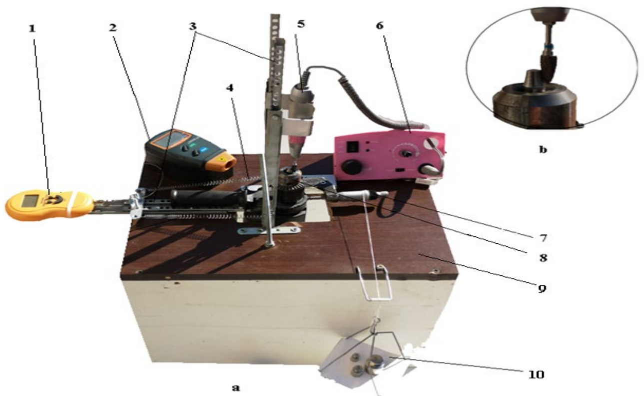


Fig. 4.39 Stand for dental milling tests: overview of stand (a): 1 - dynamometer, 2 - tachometer, 3 - mobile support; 4 - resort; 5 - micromotor; 6 - speed variator; 7 - micrometer; 8 - chuck; 9 - support table; 10- plate; detail view of material clamp and tooth cutter (b)

4.8 Experimental research program

Through the experimental research program, the following were imposed:

- determination of the characteristic sizes of the standard dental cutter and of the dental materials subjected to the experimental research before and after testing;
- preparation of the stand for the experimental tests;

- establishing working regimes (rotational speed, time, pressing force, cutting advance);
- obtaining experimental results.

4.8.1 Determination of the characteristic sizes of the standard cutter subjected to research

The experimental researches considered, first of all, the determination of the mass, the characteristic angles, the area of the top circle of the standard dental cutter subjected to research, respectively of the processed dental materials, before the testing.

Tables 4.2 and 4.3 show the mass, characteristic angles and top circle area of the standard dental cutter (Table 4.2), respectively the mass and dimensions of the standard dental material under test (Table 4.3), before testing.

Table 4.2

Mass, the characteristic angles of the standard dental cutter researched

Cutter type	Mass, m [g]	Setting angle, α [º]	Sharpening angle, β [º]	Clearance angle, γ [º]	Peak circle area, A_{cp} [μm^2]
Standard	4,701	37.74	61.48	9.90	441.71

Table 4.3

Mass and dimensions of standard dental material subjected to processing

Name	Mass, [g]	Overall length, [*mm*]	Diameter, [*mm*]
Standard	6.18	13.00	8.60

The samples of the dental material used for the tests are made of nickel-chromium alloy (Ni - Cr) with the following composition: Ni 77.95% (max); Cr 12.60%; Mo 5.00%; At 2.90%; Be 1.95% (max); Co 0.45%; Ti 0.35% and the following physical properties: tensile strength 196000 psi (1352 MPa); twist resistance: 21,500 psi (838 MPa); elongation 18%; Brinell hardness 2350 MPa; density 7.9 g / cm3; expansion coefficient of 14 x 10-6; melting temperature is in the range 1160 - 1275 oC [33].

4.8.2 Preparation of the stand for the experimental tests

Before starting the experimental stand (shown in Fig. 4.39 of paragraph 4.8, with all the components), for the experimental tests, it requires prior preparation. After choosing, the type of cutters and dental materials used in the experimental determinations and photographed at the macro level, 100: 1 scale (see fig. 4.2 and fig. 4.43), measurements were performed by weighing both the dental material and the cutters. used for experimental tests (tests), and then fixing them in the support chucks (9) of the micromotors (6) (see Fig. 4.39).

For the dental cutters, a standard cutter of the same type and model shown in fig 4.2 was chosen, which was then sectioned (see fig. 4.3) and the placement angles (α), sharpening (β), clearance (γ) were measured.) and the area of the top circle (A_{cp}) of the cutting blades, which are also the subject of the experimental research program (see Fig. 4.40 - 4.43 and Table 4.2).

4.8.3 Establishment of working regimes for the processing of the material with the dental cutter taken as a standard

After establishing the working regimes (rotational speed, time, pressing force, feed) for experimental research, the dental cutters were fixed in turn in the support chuck of the micromotor (5) (see fig. 4.39), which ensures the movement of rotation to the pre-set operating mode, respectively the milling material was mounted in the support chuck (8).

Then, the pressing force between the active part of the dental milling cutter and the milling material, the time for testing and the speed with which the milling is performed, were fixed. This was followed by the establishment of the rotation speed of the milling material and its advance by placing on the plate (10) (see fig 4.39) the weights that ensure the pressing force and that actuate the micrometric screw.

At the expiration of the time initially established for testing (1, 2, 3, 3.5 and 4 hours respectively) for each of the established speeds (7000, 12000, 20000, 35000 rpm), the weighing of the dental cutters used for the experimental tests was performed. They were then sectioned using the Lobotom 5 cutting machine with Bosh Multi Wheel cutting disc (see fig. 4.4) and the angles of the cutting slats were measured using the Olyimpus metallographic microscope, equipped with Stream Essential camera and image processing software (Fig. 4.45).

For the tests were used one hundred dental cutters grouped in four groups of 25 for each speed, respectively 7000, 12000, 20000 and 35000 rpm. In each group, five tests were performed for the established working time, respectively 1, 2, 3, 3.5 and 4 hours. The pressing force and the feed were kept constant. Working modes: rotational speed, time, pressing force and feed are given in Table 4.4.

The tests were performed in a number of five, repeated for each group of milling cutters, at the same established working regime. Following the experimental tests and the performance of the measurements, the results obtained regarding the wear behavior of the dental cutters subjected to experimental research, were taken into account, the most representative values of wear and presented in tables 4.5 and 4.6 of the thesis.

The main results, obtained from experimental tests, by measurement in the laboratory are given in this chapter. During the experiments, the values of the main parameters that highlighted the wear of the dental cutter were measured at the established time intervals: mass of material lost by wear of the dental cutter according to table 4.5, placement angle α, clearance γ, sharpening β and the area of the circle at the top, A_{cp}.

Rapid wear of dental cutters leads to higher prices for laboratory work and dental operations. Being fine mechanical tools, used for fine and technically delicate operations, made of expensive materials, rapid wear has led to studies and research in the hope that an extension of their life or even an optimization of their operation can be obtained.

We approached the problem of dental milling cutters for practical purposes (optimization or improvement of operating regimes, constructive solutions, possibly the materials from which they are built, formulating criteria for replacing used milling cutters). The phenomenon of wear of dental cutters is a classic phenomenon in physics, frequently in the theory of metal cutting, in the theory of parts wear, in drilling processes, in the immediate vicinity of the theory of friction. Therefore, some laws of the phenomenon of wear that occur in bodies in contact and with relative motion, can be used as a source of inspiration. In order to apply the laws of the phenomenon of wear when studying dental cutters, a list of important parameters must be designated in describing the phenomenon with which effective combinations can be created to estimate the efficiency of the working process of dental cutters.

The material with which the experiments were performed consists of the dental cutters tested in these experiments and the dental material to be milled. Some types of experimentally tested tooth cutters are presented in Table 4.7, together with their more important dimensional characteristics. The paper [31] presents the experimental methodology for testing dental cutters, together with the necessary components and / or accessories.

The experimental method, regarding the wear behavior of dental cutters, was preceded by metallographic and chemical analyzes, but also mechanical analyzes of the materials used. Because wear is a process that depends not only on the material of the tooth cutter, but also on the dental material processed, as well as the parameters of the working process (rotational speed, pressing force, feed, position, etc.) was mechanical and chemical characterization of the dental materials used is also required.

During the test program, milling tests were performed on samples of Cr-Ni alloy (see fig. 4.44) for four hours, at four rotational speeds of the dental milling cutter, the measurements being made according to the research program at 1, 2, 3, 3.5 and 4 hours, respectively. After four hours of operation, it was found that for the set pressing force of 38.88 N, the tooth cutter no longer advances in material, the feed rate of the tooth cutter in material measured by the displacement of the micrometric screw relative to the unit of time remained constant.

The list of functional parameters observed in the experimental tests and the units of measurement of these parameters is presented in table 4.8

Table 4.8

Work process parameters

Parameter	Notation	Unit of measurement	Parameter type
Time	t	sec, min, hours	Command
Mass lost due to wear of the dental cutter	m_{fw}	g	Entrance exit
Milled table (of dental material)	mm	g	Qualitative
Sitting angle	α	degree	Entrance exit
Clearance angle	γ	degree	Entrance exit
Sharpening angle	β	degree	Entrance exit
Advance	s		Command
The area of the top circle	A_{cp}	m^2	Entrance exit
Rotational speed of the dental cutter	n	rpm	Command

4.9 Analysis of experimental results

The experimental tests consisted in the records of the numerical values of the main input, control and input / output parameters, mentioned in table 4.8. Initially, they were recorded in numerical form, but for ease of interpretation, the dependence of the tabulated parameters as a function of time and rotation speed of the dental cutter was represented graphically. The graphical representations are shown in fig. 4.47, 4.48, 4.49, 4.50, 4.52 and 4.52.

a) Mass of material removed by wear

The main indicator of dental cutter wear is the mass removed (lost) by wear. The experiments recorded the variation of this parameter at the five operating times, previously established (respectively 1, 2, 3, 3.5 and 4 hours of operation), for four values of the speed of the dental cutter (respectively 7000, 12000, 20000, and 35000 rpm). The results were stored in the Excel numeric database. A synthetic representation of these can be seen in fig. 4.46.

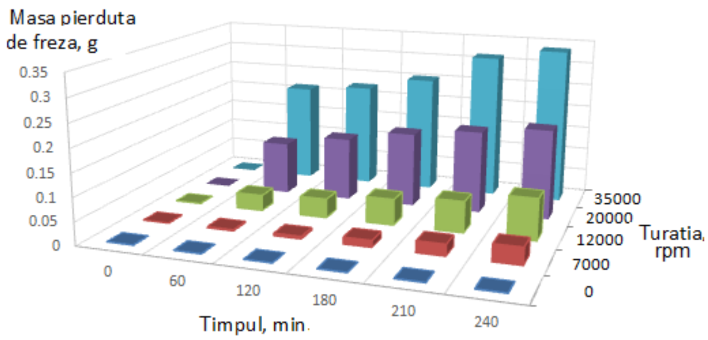


Fig. 4.46 Evolution of the mass of the tooth cutter removed by wear in the working process. depending on time, t and speed n

According to the experimental methodology, the mass of the material lost by the dental cutter due to wear, becomes a function of two variables [22]:

$$m_{fw} = m_{fw}(t, n), \tag{4.4}$$

the parameters being noted according to table 4.8. The determination of some explicit expressions of this function is the subject of the statistical analysis of the experimental results or of a theoretical analysis of dimensional analysis.

From fig. 4.46 it is observed that the function (4.4) is nonlinear with both time, *t* and speed, *n* (with both variables). At the same time, on the spatial representation in fig. 4.46 it is observed that the upper faces of prisms of the same color, are not arranged after a straight line. The observation becomes obvious (clearer), in the graphic representations from fig. 4.47 and 4.48 as a function of a single independent variable, where the variation of the mass of the tooth cutter lost by wear over time, at its four speeds is nonlinear. Thus, in fig. 4.47 is presented the variation of the mass of material lost by the dental cutter by wear as a function of time, for four rotational speeds of the dental cutter, and in fig. 4.48 shows the variation of the mass of material lost by the dental cutter by wear depending on the rotational speed of the dental cutter, measured at four different time periods. It is observed that the mass of material lost through wear increases with increasing speed of rotation of the dental cutter, as well as with working time (operation).

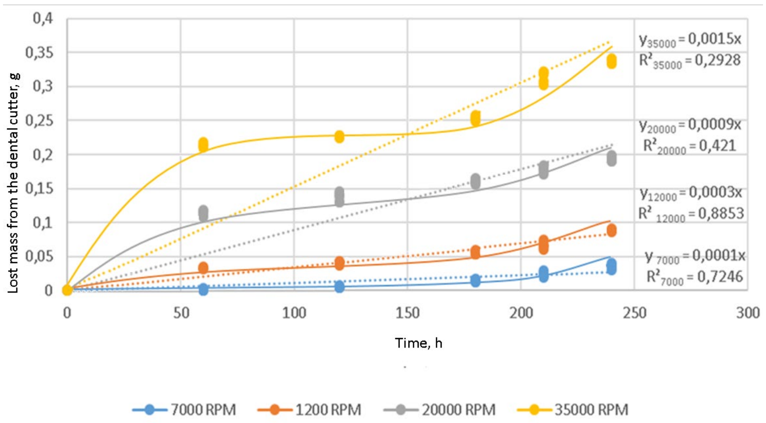


Fig. 4.47 Variation of tooth cutter mass removed by wear in operation five working times and four rotational speeds

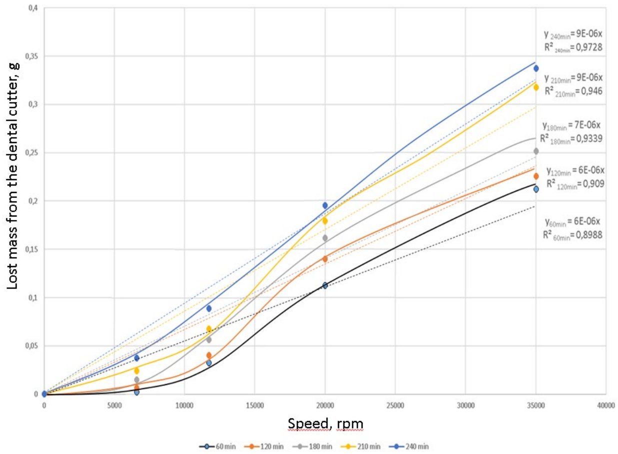


Fig. 4.48 Variation of tooth cutter mass removed by wear as a function of rotational speed and working time

Regarding the modification of the mass lost by the dental cutter with its rotational speed [27], a nonlinear variation is found for low rotational speeds (below 10000 rpm) and, according to the experimental results, it tends to be linear for rotational speeds over 10,000 rpm, which can be seen from fig. 4.48.

The extension of the graphics between 0 and 7000 rpm corresponds to the hypothesis that the mechanical wear does not take place at zero speed. It was considered the hypothesis that at zero speed, the dental cutter in contact with the dental material does not produce removal of the material, so it does not wear out. By this hypothesis we added the origin of the five measuring points on all curves, necessary for interpolation, as will be seen in Chapter 5.

b) Variation of the angle of placement, clearance and sharpening of the tooth cutter in the working process

Experimental results similar to those of the mass of material lost by the dental milling by wear (in the working process) are shown in fig. 4.49, for the variation of the seating angle - α, fig. 4.50 of the clearance angle - γ, and fig. 4.51 of the sharpening angle - β, depending on the time and speed of rotation of the tooth cutter.

The variation of the seating angle, α, with time, for four values of the rotation speed of the dental cutter is presented in fig. 4.49. In general, it can be stated that this angle decreases over time and we notice that the decrease is more intense, the higher the rotational speed of the dental cutter.

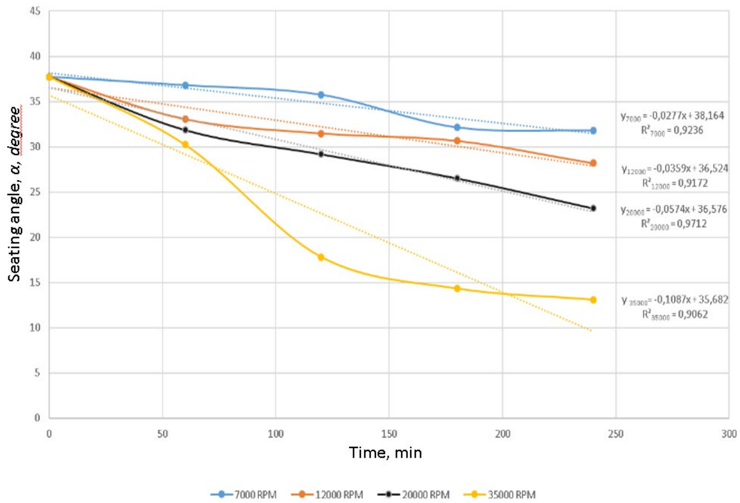


Fig. 4.49 Change of seating angle, α, as a function of time and of the rotational speed of the dental cutter

Figure 4.50 shows the variation of the clearance angle, γ, over time, for four values of the rotational speed of the dental cutter. It is observed that this angle increases over time with small oscillations in the range of 60-180 min and, at the same time, increases with increasing speed of rotation of the dental cutter. Thus, it is worth mentioning here, the following characteristics regarding the evolution of wear, confirmed by practice: wear accumulates over time and increases with the length of the friction path, without the process always having a linear evolution. At the beginning of operation, in new friction pairs, the intensity or speed of wear increases relatively quickly, due to the initial surface conditions that tend to adapt.

This period is reflected by zone I, fig. 4.50, considered to be the running-in period; the second period, of long duration, from about 60 min to about 180 min, according to fig. 4.50, is the period of stable or normal wear (normal operation period); the third period, when finally the wear becomes destructive, decreases the advance speed of the tool measured with the micrometric screw, the working process develops with abnormal noises, situation in which the friction pair is taken out of operation, for which it is necessary disassembly and replacement of the dental cutter. The third period is also called the period of damage wear [26].

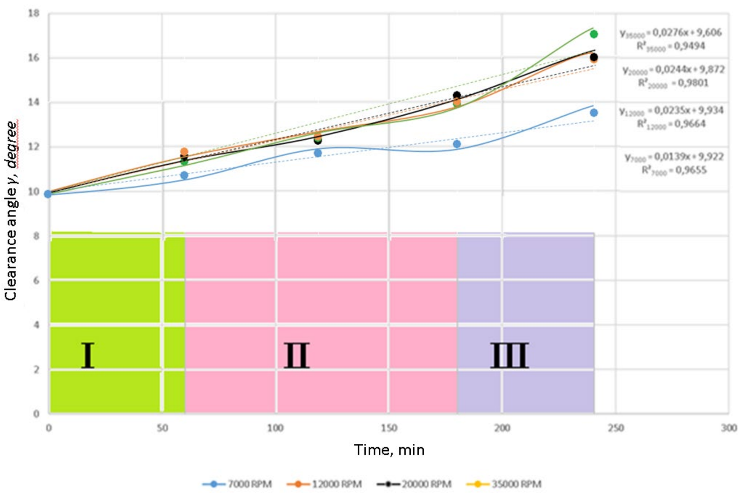


Fig. 4.50 Changing the clearance angle γ, as a function of time and of the rotational speed of the dental cutter

The variation of the sharpening angle, β, as a function of time, for the same four values of the rotation speed of the dental cutter is represented in fig. 4.51.

It is observed that the sharpening angle β, increases with the increase of the operating time, and of the rotation speed of the dental cutter, the increase being slower (approximately linear and with slope, relatively the same) at average rotation speeds (7000 and 12000 rpm), respectively faster for high rotational speeds of the dental cutter (20000 and 35000 rpm).

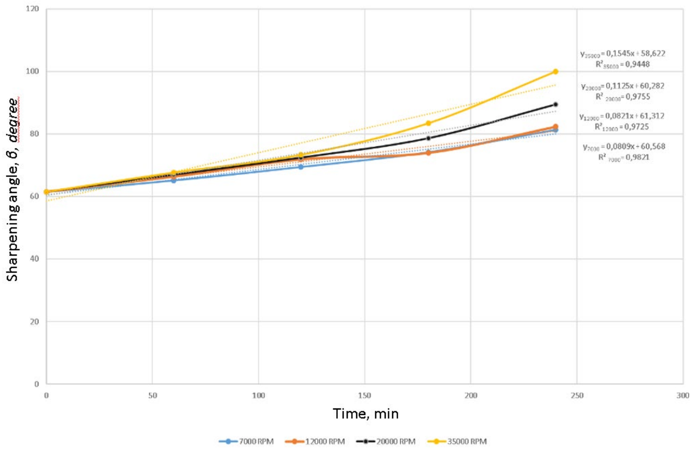


Fig. 4.51 Changing the sharpening angle, β, as a function of time and the rotational speed of the dental cutter

Finally, the variation of the area (surface) of the circle at the top, A_{cp}, as a function of time, for four values of the rotational speed of the dental cutter is presented in fig. 4.52.

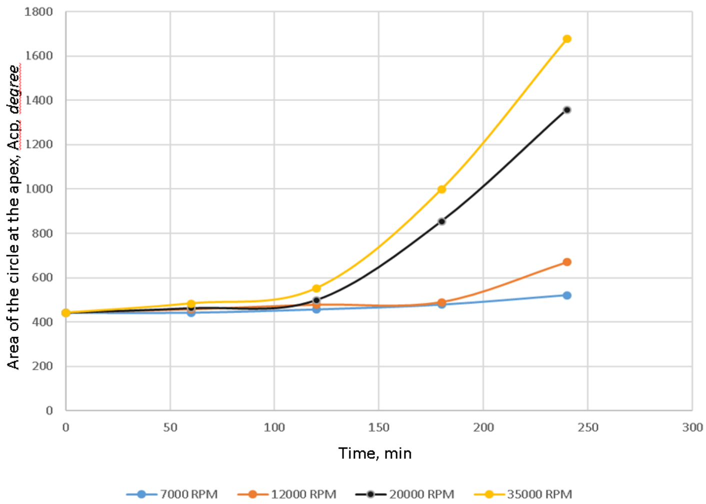


Fig. 4.52 Evolution of the area of the circle at the apex, A_{cp}, of a dental cutter, depending on the time and speed of the dental cutter

It is observed that the area of the peak circle, A_{cp}, increases with running time (working) and rotational speed, slower for medium rotational speeds (7000 and 12000 rpm) and more pronounced at higher speeds (35000 rpm), after a 180 min operation of the dental cutter. It is also observed that at average rotational speeds of the dental cutter (7000 and 12000 rpm) the increase in time is approximately linear with a relatively small slope (the slope increases with increasing rotational speed of the dental cutter), and at high rotational speeds of the dental cutter (35000 rpm), the area of the top circle, A_{cp}, has an approximately linear increase, with a small amplitude oscillation in the operating range of 60 ... 180 min, and after 180 min it shows a relatively rapid increase. The faster increase in time of the peak circle area, A_{cp}, at the rotational speed of 35000 rpm of the dental cutter resulting from the analysis of experimental data, justifies the change in the value of the sharpening angle, β, which leads to increased wear and corresponds to period III (see Fig. 4.50), i.e. of the emergency wear. Also, the experimental data show an appreciable deviation from the average rotational speeds (7000 and 12000 rpm), which implies the need for additional experimental analysis.

4.10 Statistical-mathematical modeling of the wear phenomenon in dental cutters based on experimental results (interpolations, functions, optimal points)

One parameter that contributes to the generation of wear, taken into account, is the angular space θ (circular friction length), expressed as a function of time, t and angular velocity of the milling cutter, ω, given by the relation (4.5):

$$\theta = t \cdot \omega \,, \quad [\mathrm{rad}], \tag{4.5}$$

The parameter, θ has the size of an angle, practically the angular distance traveled at the rotation of the dental cutter, and the angular velocity of the dental cutter, ω from the relation (4.5) expressed as a function of the speed, n of the dental cutter is given by the relation:

$$\omega = \frac{\pi n}{30} \,, \quad [\mathrm{rad \cdot s^{-1}}] \,, \tag{4.6}$$

The interpretation of relations (4.5) and (4.6) reflects the similarity of the phenomenon of wear of the active part of the dental cutter, with the phenomenon of wear of vehicle tires, for example. Wear itself is a more complex phenomenon, a phenomenon in which two components participate equally, even if one is active and one is passive. For these reasons, the set of parameters that characterize the wear phenomenon must be completed with the corresponding parameters of the milled material, here the passive component, respectively with the chemical and mechanical characteristics presented in paragraph 4.9.1 for the milled material (Ni-Cr), respectively the mechanical characteristics, structural and chemical properties, presented in paragraphs 4.4.1, 4.5.2 and 4.7 for the dental cutter, ie the active component.

If the mass of the milled dental material is m_m, the value of this mass when the operator declares that the dental milling becomes inefficient is very important in evaluating the quality of the milling cutter, more precisely the milling process, because it can be determined how much material the milling machine processed. .

A very important property of the materials that interact in the milling process is their hardness, both of the dental cutter and of the milled material.

If we denote with H_{fw} and H_m the hardness of the dental milling material, respectively of the dental material subjected to the milling operation, then empirical relations can be established, based on the dimensional analysis between the parameters of the milling process. One of these relations is of the form:

$$\frac{m_{fw}}{m_m} = f\left(\alpha, \beta, \gamma, S, \omega, H_{fw}, H_m\right) , \tag{4.7}$$

where:

$$S = \frac{F}{p} \quad [mm^2], \tag{4.8}$$

in which:

• S is the contact surface between the milling cutter and the material being milled,
• F is the pressure of the tooth cutter on the contact material,
• p is the contact pressure;
• m_{fw} is the mass of the dental cutter after the working process.

It was found, from the results of the experiments described above, that the three angles of placement, α, sharpening, β, clearance, γ (see Table 4.8), depend on the rotational speed, ω, then it can be assumed that the size of the contact surface, S depends on the same variable ω, ie:

$$\alpha = \alpha(\omega),\ \beta = \beta(\omega),\ \gamma = \gamma(\omega),\ S = S(\omega)\ , \tag{4.9}$$

The relationships (4.9) can be described analytically by the resulting interpolation curves, using statistical analysis of the experimental results, except for the value of the contact area, s, for which additional measurements should be made, or additional deductions / modeling are required. Based on the relationships (4.8), the relationship (4.7) becomes:

$$\frac{m_{fw}}{m_m} = f\left(\omega, H_{fw}, H_m\right) \qquad , \tag{4.10}$$

If experimentally, the pressing force of the active part of the dental cutter, F, and the contact pressure, p, respectively, can be controlled, then the relation (4.10) can be written as follows:

$$\frac{m_{fw}}{m_m} = f\left(\omega, F, p, H_{fw}, H_m\right) , \tag{4.11}$$

thus, it is observed that the force of pressing the milling cutter on the dental material subjected to milling, F, also appears as an important parameter of process control.

An elementary variant of the relation (4.11), which can be tested for experimental data, supplemented with information about the size of the contact surface, S, or about the force, F and the contact pressure, p, is the following:

$$\frac{m_{fw}}{m_m} = f(\omega) \cdot \frac{F}{p} \cdot \frac{H_{fw}}{H_m} , \tag{4.12}$$

where f (ω) is the empirical function that has the inverse value of the size of a surface, being determined from experimental data. In the proposed statistical analysis we will test representations of the relation (4.12) according to several parameters, namely:

$$\frac{m_{fw}}{m_m} = \left(f(\omega) \cdot \frac{F}{p}\right)^{\mu} \cdot \left(\frac{H_{fw}}{H_m}\right)^{\nu} , \tag{4.13}$$

where: μ and ν are dimensionless parametric exponents that can be determined by statistical methods (classical least squares method or by numerical minimization of the attached function).

An alternative way to find relationships between the parameters of the dental milling process can follow Archard's relationship [3] and the reasoning by which it was obtained.

The results obtained from the experimental research on the wear in the work process of the dental cutter-dental material couple, constitute the data that are processed and modeled statistically-mathematically in this paper, and presented above (see table 4.5, 4.6)

Experimental results similar to those presented above, are also presented in ref. [5].

In general, the phenomenon of contact surface wear, in relative motion, is difficult to model by a purely theoretical approach, although not impossible [10, 23]. In the case of the working process of dental milling cutters, the phenomenon is, at least up to an appreciable wear of the active part of the dental milling cutter, closer to the process of milling by cutting metals.

In this paper we used a deterministic model, differential for the working process of dental cutters (model presented in the paper [7]), on the phenomenon of wear of the lamellae of the active part of the dental cutter.

For the statistical-mathematical modeling the numerical results of the milling experiments with the dental milling cutters, described above were used (see tables 4.4, 4.5 and 4.6). The results of the experiments demonstrate the dependence of time and speed of rotation of the dental cutter, the geometric characteristics of the slats of the active part of the dental cutter and the mass of material removed by wear (see Table 4.5, and 4.6).

Statistical-mathematical analysis, used for processing and modeling the results obtained experimentally is based on polynomial interpolation using the least squares method. Due to the relatively small amount of results, neither broader methods of statistical analysis nor interpolation polynomials of degrees higher than the third degree can be approached. However, as will be seen from the results obtained by modeling, the third degree is sufficient to describe the phenomenon of wear of the active part of the dental cutters. Thus, the general mathematical relation of interpolation polynomials, written in canonical form is the following:

$$q(t,\omega) = \sum_{i=0}^{3}\sum_{j=0}^{3} c_{ij} t^i \omega^j \,, \tag{4.14}$$

which developed to the third degree, becomes:

$$q(t,\omega) = c_{00}t^0\omega^0 + c_{10}t^1\omega^0 + c_{20}t^2\omega^0 + c_{30}t^3\omega^0 + c_{01}t^0\omega^1 + c_{02}t^0\omega^2 + c_{03}t^0\omega^3, \tag{4.15}$$

as sufficient to describe the phenomenon of wear of the active part of the dental cutters, and q is one of the five interpolated parameters (m_{fw}, α, β, γ, A_{cp}).

The synthesis of the interpolation results by the method of least squares for the five measured parameters (see table 4.8) during the experimental tests is given in tables 4.9. 4.10 and 4.11 and contain the coefficients of polynomials with two variables (time, t, and rotational speed of the dental cutter, ω, implicitly and of the active part of the dental cutter, c00 ... c03), as well as the average of the quadratic errors, ε, which prioritizes approximation performance. The coefficients of the polynomials were calculated with the MathCad program using the least squares method.

The polynomial coefficients are double indexed, the first index (example: 1 of c10) represents the exponent of the power of the temporal variable (time, t). the second index (example*: 0 of* c_{10}) represents the rotational speed, ω.

For the calculation of the error, ε, the relation (4.16) was used:

$$\varepsilon = 100 \cdot \frac{\sqrt{\left(y_w - y(x_w)\right)^2}}{\bar{y} \cdot N}\,, \tag{4.16}$$

where:

- $y_w, w = 1, \ldots, N$ are the experimental data for the dependent variable, e.g. α, γ, β, A_{cp}, and m_{fw};
- $x_w = t_w, \omega_w$ is the data string of the independent variable, for example t and ω;
- N being the number of experimental data;

- $\bar{y}$ is the average value of the experimental data for the string of the dependent variable.

Applying the general mathematical relation (4.14) for the parameters measured and given in tables 4.9, 4.10 and 4.11, when moving to the canonical form of interpolation polynomials, we obtain, for example:

• for - the values by interpolation of the polynomial (function) in table 3.9:

$$m_{fw}(t,\omega) = \sum_{i=0}^{3}\sum_{j=0}^{3} c_{ij} t^i \omega^j \,, \qquad (4.17)$$

that is:

$$m_{fw}(t,\omega) = 6.744\cdot10^{-5}t - 5.699\cdot10^{-4}\omega - 1.028\cdot10^{-8}t\omega - 8.736\cdot10^{-9}t^2 + 6.156\cdot10^{-7}\omega^2$$
$$+1.762\cdot10^{-12}t^2\omega - 1.82\cdot10^{-12}t\omega^2 + 3.37\cdot10^{-13}t^3 - 1.038\cdot10^{-10}\omega^3\,, \qquad (4.18)$$

Table 4.9

Coefficients and interpolation errors for parameters

Polynomial coefficients	***m**$_{fw}$* – interpolation values of the degree polynomial (function):		
	Gradul I	Gradul II	Gradul III
c_{00}	-0.315	-0.003346	0
c_{10}	$1.746\cdot10^{-5}$	$-6.150\cdot10^{-5}$	$6.744\cdot10^{-5}$
c_{01}	$3.866\cdot10^{-4}$	$2.275\cdot10^{-4}$	$-5.699\cdot10^{-4}$
c_{11}	0	$1.333\cdot10^{-8}$	$-1.028\cdot10^{-8}$
c_{20}	0	$3.792\cdot10^{-9}$	$-8.736\cdot10^{-9}$
c_{02}	0	$1.518\cdot10^{-8}$	$6.156\cdot10^{-7}$
c_{21}	0	0	$1.762\cdot10^{-12}$
c_{12}	0	0	$-1.82\cdot10^{-12}$
c_{30}	0	0	$3.37\cdot10^{-13}$
c_{03}	0	0	$-1.038\cdot10^{-10}$
ε, %	7.828	1.733	0.486

Table 4.10

Polynomial coefficients and interpolation errors for angular parameters. *α* and *γ*, of the dental cutters

Polynomial coefficients	*α* – interpolation values of the polynomial (function) of degree:			*γ* – interpolation values of the polynomial (function) of degree:		
	Gradul I	Gradul II	Gradul III	Gradul I	Gradul II	Gradul III
c_{00}	41.267	36.889	35.74	9.314	9.771	9.9
c_{10}	$-5.692\cdot10^{-4}$	$-5.517\cdot10^{-4}$	$-3.071\cdot10^{-4}$	$3.452\cdot10^{-4}$	$-3.661\cdot10^{-4}$	$6.366\cdot10^{-4}$
c_{01}	$-4.597\cdot10^{-3}$	$1.74\cdot10^{-3}$	0.012	$3.614\cdot10^{-4}$	$3.295\cdot10^{-3}$	$-2.627\cdot10^{-3}$
c_{11}	0	$-4.39\cdot10^{-7}$	$-7.913\cdot10^{-7}$	0	$8.569\cdot10^{-8}$	$3.242\cdot10^{-7}$
c_{20}	0	$3.374\cdot10^{-8}$	$2.649\cdot10^{-8}$	0	$3.172\cdot10^{-8}$	$-1.031\cdot10^{-7}$
c_{02}	0	$-6.156\cdot10^{-7}$	$-1.094\cdot10^{-5}$	0	$-8.027\cdot10^{-7}$	$2.276\cdot10^{-6}$
c_{21}	0	0	$7.75\cdot10^{-11}$	0	0	$8.455\cdot10^{-12}$
c_{12}	0	0	$-2.152\cdot10^{-10}$	0	0	$-8.718\cdot10^{-11}$
c_{30}	0	0	$-3.775\cdot10^{-12}$	0	0	$4.251\cdot10^{-}$

						12
c_{03}	0	0	$2.354\cdot10^{-9}$	0	0	$-4.264\cdot10^{-10}$
ε, %	3.141	1.679	0.649	1.735	0.668	0.271

Tabelul 4.11

Polynomial coefficients and interpolation errors for the angular parameter, β, and the area of the top circle, A_{cp}

Polynomial coefficients	β – interpolation values of the polynomial (function) of degree:			A_{cp} – interpolation values of the polynomial (function) of degree:		
	Gradul I	Gradul II	Gradul III	Gradul I	Gradul II	Gradul III
c_{00}	56.179	62.58	9.9	366.251	410.115	441.71
c_{10}	$1.701\cdot10^{-3}$	$-2.174\cdot10^{-4}$	$6.366\cdot10^{-4}$	0.018	-0.053	-0.036
c_{01}	$2.477\cdot10^{-3}$	$1.647\cdot10^{-3}$	$-2.627\cdot10^{-3}$	0.012	0.269	0.325
c_{11}	0	$4.964\cdot10^{-7}$	$3.242\cdot10^{-7}$	0	$3.208\cdot10^{-8}$	$1.478\cdot10^{-4}$
c_{20}	0	$7.104\cdot10^{-8}$	$-1.031\cdot10^{-7}$	0	$4.048\cdot10^{-6}$	$-1.103\cdot10^{-5}$
c_{02}	0	$-6.623\cdot10^{-7}$	$2.276\cdot10^{-6}$	0	$-5.541\cdot10^{-5}$	$-6.072\cdot10^{-4}$
c_{21}	0	0	$8.455\cdot10^{-12}$	0	0	$-1.38\cdot10^{-9}$
c_{12}	0	0	$-8.718\cdot10^{-11}$	0	0	$-2.732\cdot10^{-8}$
c_{30}	0	0	$4.251\cdot10^{-12}$	0	0	$6.17\cdot10^{-10}$
c_{03}	0	0	$-4.264\cdot10^{-10}$	0	0	$1.359\cdot10^{-7}$
. %	1.417	0.565	0.271	5.453	4.478	2.675

Thus, the variation of the mass of the active part of the dental cutter, lost (removed) in percentage, by wear, during the milling (working) process is presented in fig. 4.53.

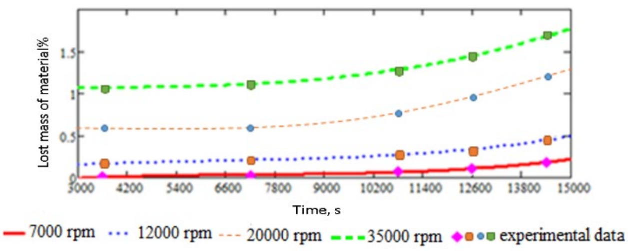


Fig. 4.53 Variation over time of the material of the active part of the tooth cutter lost through wear, for four values of the rotational speed described by the third degree interpolation polynomial

The four curves are given by the third degree polynomial equations (according to relation (4.14) and (4.17)), for four values of the rotational speed of the dental cutter. Also, in fig. 4.53 are also represented the points corresponding to the experimental data, based on which the interpolation polynomials were found.

From fig. 4.53 it is observed that the mass lost by wear by the somalogical milling cutter is slightly increasing over time and at the same time increases with the increase of the rotational speed of the dental milling cutter (except for some very weakly visible minimum points at lower rotational speeds).

Thus, after 4 hours of operation, the mass lost through wear is approximately 0.2% of the initial mass of the dental cutter at a speed of 7000 rpm, 0.4% at a speed of 12000 rpm, 0.85% for a speed of 20,000 rpm, respectively 1.55% at a speed of 35000 rpm, so a very small percentage increase, which proves the above statement.

To avoid the use of these functions for extrapolation purposes, with regard to the calculation of wear loss by wear at rotational speeds of less than 7000 rpm or greater than 35000 rpm, respectively for time intervals of more than 4 hours (14400 s), the speed of rotation of the dental cutter has a greater influence on the wear of the flanks (lamellae) compared to the temporal parameter, t, a finding similar to what was presented in ref. [6].

By the graphical representation of Fig. 4.54 were obtained the surfaces that geometrically represent the interpolation functions of degree I (a portion of the flat surface, blue), of degree II (a portion of the parabolic surface, green) and of degree III (a portion of cubic surface, red) , depending on the two variables: time, *t* in (sec) and angular speed of the tooth cutter, *ω*, in (rad / s). The shape of the resulting curves is given by the degree of interpolation functions, respectively grade I for flat surfaces, grade II for parabolic surfaces and grade 3 for cubic surfaces. On the same figure (see fig. 4.54) the points corresponding to the experimental data are observed, represented as point centers in the shape of a rhombus.

The interpolation functions were exemplified for the case of the variation of the mass lost by the active part of the dental cutter by wear, as functions of time and angular velocity of the dental cutter. The same methodology can be applied (as studies, interpolations, results, discussions and graphical representations) for the other four process parameters (see table 4.8) that characterize the wear of the active part of the dental cutter.

Interpolation functions for process parameters that characterize the wear of the active part of the dental cutter are used to establish possible extreme points (optimal reference points) or to estimate any asymptotic behavior with respect to large values as a function of time and rotational speed (which may suggests a quantified limit, useful for the decision to replace the dental cutter used).

Critical or asymptotic points, which are determined in this way, can only be accepted after experimental validation, ie after a series of new experiments.

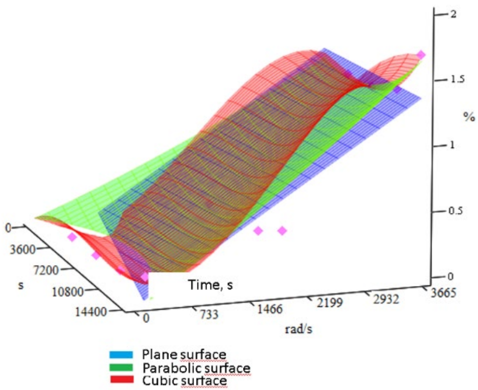


Fig. 4.54 Geometric representation of degree I, II and III interpolation functions, with two variables, time, t and angular velocity, *ω*, for the lost mass the active part of the tooth cutter in the working process

It should be noted that the results presented above are limited to the type of dental cutters that have been tested.

Polynomial interpolation is a simple case, generally used in the numerical processing of experimental data, especially when no particular aspects of the studied phenomenon are known. The interpolation polynomials for the system-dependent parameters presented above (see table 4.8) in this case, are accurate for what we are looking for, but from a physical point of view, they often do not have a physical interpretation. This means that the quantitative accumulations produced by polynomial interpolations do not generally lead to qualitative progress that refers to new theoretical explanations and additional applications.

In the following, an example of interpolation will be given by a function based on two hypotheses derived from the experience gained during experimental research on the wear processes of cutting or polishing devices, namely:

1) is considered a function with the exponential component (function 4.19), which has an asymptotic behavior for infinite values of the variables t, and n or ω (which models stopping the growth of lost mass after reaching critical wear) and is canceled at the origin (which what is expected, in the sense that for working time equal to zero or zero rotation speed, the active part of the dental cutter does not change). The expression of this function is elementary and depends on a single variable, θ:

$$\psi(\theta, c, d) = c\left(1 - e^{-d \cdot \theta}\right), \tag{4.19}$$

where:

- c and d are the model parameters;
- θ is the independent parameter (function variable); (eg time, rotation speed);
- e is the basis of the natural logarithm.

2) the idea of using a single independent variable, θ starting from the two seemingly independent variables, time, t and angular velocity, ω, of the dental cutter, results from the fact that their product is the rotation angle of the dental cutter, θ (angular space traversed in the working process or circular friction length), whose expression is given by the relation (4.5), ie: $\theta = t\omega$.

Also, the hypotheses are in accordance with the observations resulting from the experiments described above (see paragraphs 4.9.4 and 4.10) and in accordance with ref. [31];

For the calculation of parameter c in relation (4.19) a new hypothesis is introduced. According to the experimental observations, after a complete operating program, the dental cutter no longer cuts / removes particles / chips from the processed material. Therefore, there is a limit to the sharpening angle at which the dental cutter no longer works, more precisely, the amount of material lost / removed from the active part of the cutter by wear remains approximately constant, as does the amount of material subjected to processing.

This can be interpreted as asymptotic behavior for function (4.19). With these assumptions, the parameter of the model, c, is established on the basis of the relation:

$$c = \max_{i=1,\dots,N} m_{fw\,i}, \tag{4.20}$$

where: $m_{fw\,i}, i = 1, \dots, N$ are the experimental data for the mass of material lost by the active part of the dental cutter due to wear; N - number of experimental data.

For the calculation of the second model parameter, d, the least squares method applied to the nonlinear function (4.21) is used:

$$\Psi(d) = \sum_{i=1}^{N}\left(\psi(\theta_i, c, d) - m_{fw\,i}\right)^2, \tag{4.21}$$

where: θ_i has the meaning and expression similar to θ in relation (4.5), generalized, namely:

$$\theta_i = t_i \cdot \omega_i, \tag{4.22}$$

where: t_i, ω_i, $i = 1, \ldots, N$, are the experimental data established in advance for the working time and the angular velocity of the dental cutter (dental).

The function (4.21), being nonlinear, is numerically minimized and the value of parameter d is found for the set of experimental data available in ref. [1], namely: d = 3.5 · 〖10〗 ^(- 8). The result is c = 1.686%, according to the experimental data.

Based on these results, the graphical representation in fig. 4.55, of the mass of material lost by wear, by the active part of the dental cutter, percentage, as a function of θ (variable (independent parameter) of the function (4.19)). For comparison, the error, ε, obtained in this case is ε = 14.631%.

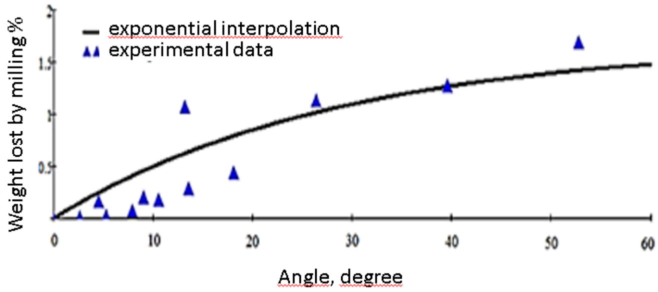


Fig. 4.55 Variation of the interpolation function (4.19) of the mass of material lost through wear by the active part of the dental cutter

By entering (4.5) in (4.19), the interpolation function with two variables is obtained:

$$\psi(t,\omega) = c(1 - e^{-d \cdot t \cdot \omega}) , \tag{4.23}$$

The function (4.23) is represented graphically, as a function of the two variables (t, ω) In fig. 4.56.

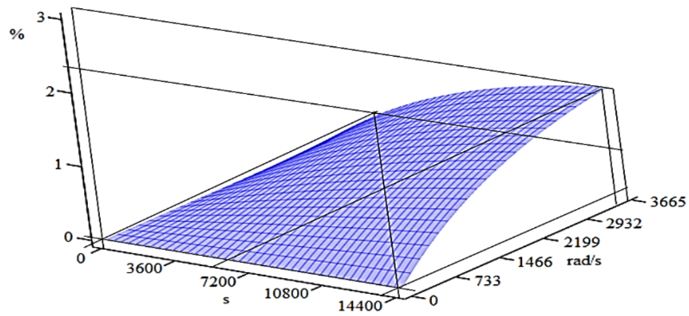


Fig. 4.56 Representation of the interpolation function (4.23) as a function of two variables, which represents the mass of material removed / lost from the dental cutter by wear

It is observed that this interpolation function for the prediction of wear of the active part of the dental cutter has an important property, namely:

$$\lim_{t \to \infty} \psi(t,\omega) = c > 0, \tag{4.24}$$

Relation (4.24) can be used to impose a decommissioning condition of the dental cutter.

For example, when a mass equal to a fraction μ of the limit value c (see relation (4.24)) is reached, the dental cutter must be declared decommissioned.

So the condition can be written in the following form:

$$e^{-d \cdot t \cdot \omega} = \mu, \ \mu \in (0, 1) , \tag{4.25}$$

From the relation (4.25) is obtained the conventional lifetime, t_μ, of the active part of the dental cutter:

$$t_\mu = \frac{\ln\frac{1}{1-\mu}}{\omega \cdot d}, \tag{4.26}$$

respectively, from relation (4.26), it results that the conventional lifetime, t_μ, thus defined, is inversely proportional to the angular velocity of the dental cutter, ω. In ref. [10], the characterization of wear on milling is done by reducing the diameter of the tool (milling cutter), on a certain contact width, characterization, which is consistent with that presented in this paper by weight loss, due to wear, in the process of work of dental cutters (dental).

CHAPTER V
RESEARCH ON THE DURABILITY AND RELIABILITY OF DENTAL CUTTERS

5.2 Presentation, estimation and expression of dental cutter defects

The durability (ability to function) and reliability of the components are the main conditions for the effective functioning of an ethnic system.

As a result of the growing interest in reliability, there has been a recent formalization of the reliability aspects. The formalization of the aspects of reliability (as a result of advanced technologies, electronics, respectively the increase of the complexity of systems in general) is manifested by establishing conditions of this nature required by the beneficiaries, registered as contractual clauses, more and more often. As a result, reliability had to be measured, forecasted and ensured. Thus, reliability programs have emerged, which enrich and complete the content of general programs aimed at increasing the quality of products. In general, the most modern description of technical systems, which is also very suitable for calculating reliability, is the systemic one. A general description of this type is given in Fig. 5.1, after [5].

Mathematically, it is the essential component of the operational safety of the system, in known working conditions including all the components that actually represent the reliability, maintenance, availability and safety of the system.

Depending on the time *R (t)*, the reliability is defined as the probability of operation without failure at the preset parameters in a time interval [0, t), respectively its value is in the range 0 and 1. In the case of complex systems, the reliability of each component is taken into account for the calculation of operational safety. The reliability may be:

- *forecast (projected)*
- *experimental (laboratory*
- *operational (effective.*
- *nominal*
- *potential [21].*

It is evaluated on components resulting from mass production.

It should be noted that the research of the thesis deals with the active part of the dental cutter and not with the entire cutter. If it deals with the whole milling cutter, the thesis should take into account, from the point of view of reliability, other component parts of the milling cutter: drive motor, bearings, dental milling cutter clamping systems, etc.

Dental milling cutters, more precisely the active part of their milling is an element without automatic restoration (irreparable), [33], after the occurrence of the malfunction or loss of working capacity. If the whole dental cutter is referred to as a machine, then it can become a restoration system, by replacing a defective element: the active part of the dental cutter, the electric motor, the transmission system.

5.2.1 Estimation of the life of the active part of the dental cutter, in relation to the sharpening angle

Such an estimate of the life of the tested dental cutter, of the cylindrical-conical type [27], made of tungsten (58.14%), in relation to the sharpening angle, β, is given in Table 5.1. The critical value of the sharpening angle was considered to be 120o, the measured value of the sharpening angle for the standard dental cutter being 61.48o and presented in Table 4.2 of Chapter 4, paragraph 4.8.1. For the estimation of the life of the dental cutter, in relation to the sharpening angle, β, at the four speeds used (see table 5.1) in the experimental tests the polynomial interpolation functions of degree I, II and III were taken into account. -the, deduced and described in Chapter 4, Subchapter 4.10 detailed in Table 4.9.

Tabelul 5.1

Lifespan of the active part of the dental cutter, for four working speeds and for three functions of interpolation of additional data

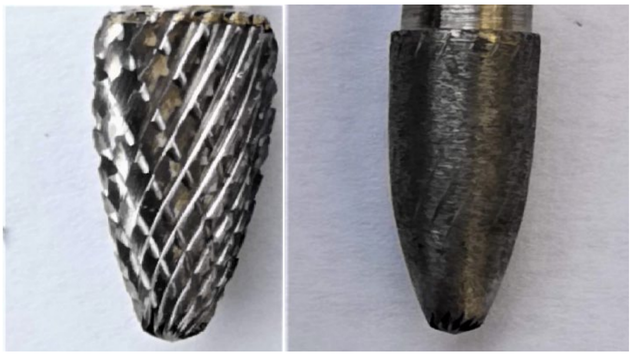
Speed, [rpm]	Lifetime in hours, given by:		
	First degree polynomial interpolation function	Second degree polynomial interpolation function	Third degree polynomial interpolation function
7000	10,128	7,557	**5,875**
12000	9,916	7,072	**5,761**
20000	9,153	6,030	**4,847**
35000	8,941	5,545	**4,733**

The most accurate results are those given by the third degree interpolation function. In addition, these results are in good agreement with the experimental results.

Similar estimates of the lifespan of the active part of the dental cutters can be made relative to the clearance angles, γ and placement, α.

5.2.2Estimation of the life of the active part of the dental cutter

To calculate the durability or service life of the active part of a dental cutter, the working time calculation formula (4.26) was used, determined on the basis of the conventional determination of a fraction of the total mass of the active part of the dental cutter, which is lost in during the work process. In order to determine the critical material fraction of the active part of the dental cutter, which can be lost through the milling process, one can start from approximately 65% of the circular crown mass of the active part of the dental cutter, determined experimentally by total wear of the lamellae. on the active side of the dental cutter followed by weighing and by the difference from the weight of the standard cutter (fig.5.2) the value of 0.522 g was obtained.



a b

Fig.5.2. Determining the mass of the circular crown of the active part of the dental cutter: a) standard dental cutter; b) standard dental cutter with the circular crown of the worn active part

Proceeding in this way, for the dental cutters tested in the laboratory, for the present doctoral thesis, the results are those given in table 5.2.

Table 5.2

Calculated lifetime of the active part of dental cutters used in experimental research

Grouping of dental cutters by speed	Dental cutter speed, rpm	Calculated life time, hours
F1.1÷F2.3	7000	11,373
F6.1÷F7.3	12000	6,634
F11.1÷F12.3	20000	3,848
F16.1÷F17.3	35000	2,275
F2.4÷F4.1	7000	10,265
F7.4÷F9.1	12000	5,988
F12.4÷F14.1	20000	3,411
F17.4÷F19.1	35000	2,053
F4.2÷F5.5	7000	12,613
F9.3÷F10.5	12000	7,358
F14.2÷F15.5	20000	4,098
F19.2÷F20.5	35000	2,523
Average calculated lifetime values, hours	7000	11,417
	12000	6,660
	20000	3,785
	35000	2,284

Example of milling group: F1.1, F1.2, F1.3, F1.4, F1.5, F2.1, F2.2, F2.3

It was found that the service life of the 100 dental cutters grouped according to table 5.2 studied shows differences in operating time depending on the operating speed, which confirms the data in the literature that the cutting speed is the main determining factor of tool life according to Taylor's principle of metal cutting technology.

Also, the use of differential equations in modeling the working process of dental cutters was also addressed in the paper [6].

5.2.3 Estimation of wear and durability of the active part of the milling cutters

In this wide context of applications, the application used in this doctoral thesis of the “prey-predator” model of Lotka-Volterra [3, 4, 12, 16, 17, 18, 21, 22, 30, to the phenomenon of interaction between the dental cutter and the milled material. The application starts from the assimilation of the dental cutter with the "predator" which extracts (removes) material from the body of the milled material, assimilated with "prey". The milling action (the action of the predator) does not remain without negative results for him, the milling material also losing particles. Both parts of this phenomenon cannot grow as a mass, an experimentally observed aspect, which turns into important hypotheses.

a) Working method and modeling

In accordance with the objective of the thesis “establishing the wear behavior of the active part of the dental milling cutters, in the working process (operation)” the phenomenon of dental milling wear will be analyzed, in accordance with the information presented in [7]. Based on experimental data taken from the literature and those obtained by the author, the model presented was applied for verification.

Among the variants that [28] proposes for the notion of wear, we have retained those that are related to the subject of this test: damage, degradation of an object or progressive modification of some physical characteristics of a part of the system during operation, according to [11], whereby "wear represents damage, gradual removal or deformation of the material on solid surfaces".

Among the many notions that define the word wear, there are the notions of mechanical erosion and physical erosion.

For certain similar aspects, from the mathematical models of some natural phenomena, we selected the biological phenomenon of "prey-predator" coexistence (interaction), expressed in the mathematical form by Lotka and Volterra, [4, 12, 17, 22].

The simplest Lotka - Volterra model is the one that contains two species, the prey and the predator. The predatory species consumes the prey species. For the application of this model, the following simplifying hypotheses are made

1) the prey population has unlimited food resources;

2) in the absence of predators, the prey population, x, will increase in proportion to its number:

$$\frac{dx}{dt} = \zeta x,\ \zeta > 0\ , \tag{5.1}$$

where: ζ - represents a real positive parameter that describes the interaction of the two species in the absence of prey, the population of predators, y, will decrease in proportion to its number:

$$\frac{dy}{dt} = -\psi y,\ \psi > 0\ , \tag{5.2}$$

where: ψ represents a real positive parameter that describes the interaction of the two species when in both populations there is a decline in the prey population, x, and an increase in the predatory population, y, will occur, both proportional to the individual interaction of the two species according to relations (5.1) and (5.2):

$$-\eta xy,\ \eta > 0 \text{ – for prey and } \Upsilon xy,\ \Upsilon > 0 \text{ – for the predator,} \tag{5.3}$$

With these hypotheses, we obtain the system of two nonlinear differential equations, of the first order that models the “prey-predator” interaction, or Lotka-Volterra:

$$\frac{dx}{dt} = \zeta x - \eta xy,\ \frac{dy}{dt} = -\psi y + \Upsilon xy,\ \zeta, \eta, \psi, \Upsilon > 0\ , \tag{5.4}$$

where: η, Υ represent real positive parameters that describe the interaction of the two species

To use this model to describe the interaction between the dental cutter and the milled dental material, some of the above hypotheses have been completed and modified. First, the mass of the dental cutter material was assimilated with the measure of the predator population and it was also denoted by *y*, and the mass of the milled dental material by the measure of the prey population, denoting its mass also by *x*. Under these conditions, the following hypothesis was accepted (true / real):

5) the mass of the dental cutter, as well as the mass of the milled dental material cannot increase. As a result, it was assumed that:

$$\zeta = \Upsilon = 0\ , \tag{5.5}$$

Then, the system of differential equations that models the contact with relative motion between the material of the dental milling machine and the milled dental material, becomes:

$$\frac{dx}{dt} = -\eta xy,\ \frac{dy}{dt} = -\psi y,\ \eta, \psi > 0\ , \tag{5.6}$$

In which: $\frac{dx}{dt}$ and $\frac{dy}{dt}$ represents the speed of variation of the masses of the dental material and of the milling head;

b) Results and comments

To solve the system of differential equations (5.6) the initial conditions are considered:

$$x(t_0) = x_0,\ y(t_0) = y_0, \tag{5.7}$$

where: t_0 is the initial time, and x_0 and y_0 the initial masses of the dental material to be milled and of the dental cutter. The solutions of the system of differential equations (5.6), taking into account the initial conditions (5.7) are:

$$x(t) = x_0 e^{\frac{\eta y_0}{\psi}\left[e^{-\psi(t-t_0)}-1\right]},\ y(t) = y_0 e^{-\psi(t-t_0)}\ , \tag{5.8}$$

which represents the mathematical modeling of the interactio*n* / contact with relative movement, dental cutter - dental material. The losses of milled dental material and of the active part of the dental cutter, ψ, result from solving the differential equations (5.8), respectively:

$$\delta x(t) = x_0 - x(t), \delta y(t) = y_0 - y(t)$$

Or:

$$\delta x(t) = x_0 \left\{1 - e^{\frac{\eta y_0}{\psi}\left[e^{-\psi(t-t_0)}-1\right]}\right\},\ \delta y(t) = y_0\left\{1 - e^{-\psi(t-t_0)}\right\}, \qquad (5.9)$$

The solutions of the system (5.8) of material loss of the dental cutter and of the milling of the dental material, contain two parameters: η and ψ. The parameters η and ψ, from the model (5.6) have the physical dimension established from the equations of the model, it results that the physical dimension of these parameters is $[\eta] = M^{-1}T^{-1}$, $[\psi] = T^{-1}$.

The mathematical model (5.8) of the interactio*n* / contact with relative motion, dental cutter - dental material does not contain an important control parameter of the work process, namely: the speed of the dental cutter, n [rpm], which is found in the expression of angular velocity, ω [rad / s] and implicitly of the rotation frequency, ν [Hz], by the relations:

$$\omega = \frac{\pi n}{30},\ \nu = \frac{\omega}{2\pi}, \qquad (5.10)$$

The idea, for the introduction of this parameter, η, in the mathematical model (5.8), is related to the physical dimension of the parameters η and ψ, involved in the process. In this way, another parameter can be introduced, which does not appear in the mathematical model (5.8), namely: the force of the milling cutter on the dental material, F. From a dimensional point of view the following expressions can be accepted for the model parameters (5.8):

$$\eta = \eta_0 \nu \cdot \frac{HVy}{HVx} \cdot \frac{g}{F},\ \psi = \psi_0 \nu \cdot \frac{HVx}{HVy} \cdot \frac{F}{y_0 g}, \qquad (5.11)$$

in which:η_0 si ψ_0 - are dimensionless constants; HVx, HVy - are the Vickers hardnesses of the milled dental material, respectively of the material from which the active part of the dental cutter is built; g - is the gravitational acceleration.

To calculate the two dimensionless constants (dimensionless parameters), η_0 and ψ_0, we will use the experimental data. Considering the model hypotheses, it is obvious that for the two dimensionless parameters only positive values will be accepted.

Using the experimental data from chapter 3, table 3.5, values are obtained for the temporal variation of the mass of the dental cutter and of the milled dental material, which allow obtaining the following values for the two dimensionless parameters:

$$\psi = 0.000000522027 s^{-1},\ \eta = 0.000007025375\, kg^{-1}s^{-1}, \qquad (5.12)$$

Note: For the calculation of the dimensionless parameters η and ψ from relations (5.12), the following values were used for the established material and working parameters that were presented in Chapter 3, Subchapter 3.5.2, Table 3.1:

$$HVx = 292\ (940\ MPa), HVy = 376\ (1211\ MPa), F = 3.5\ N, \nu = 200\ s^{-1}, g = 9.81\ ms^{-2}, \qquad (5.13)$$

the initial mass of the dental cutter being, y_0 = 4,701 g, and the mass of the processed dental material, x_0, of 6,180 g, the final values of the mass of the dental cutter varied between 4,700 g and 4,360 g and of the processed dental material varied between 6,102 g and 4,160 g. In fig. 5.3 and 5.4 are represented the temporal variations of the functions that model the evolution of the masses of the two bodies in interactio*n* / contact with relative motion: the dental milling cutter and the dental material, which is subjected to milling. In the same figures appear the experimental data that were used to estimate the dimensionless parameters of the mathematical model.

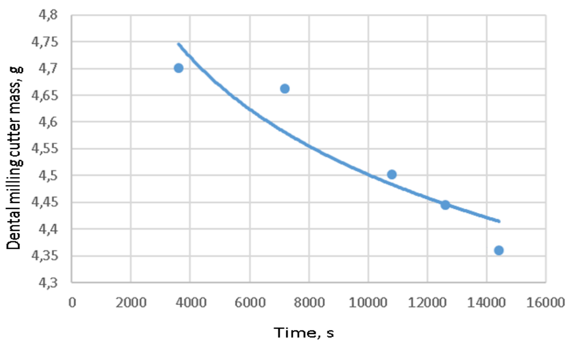


Fig. 5.3 Time variation of the mass of the dental cutter, in the working process

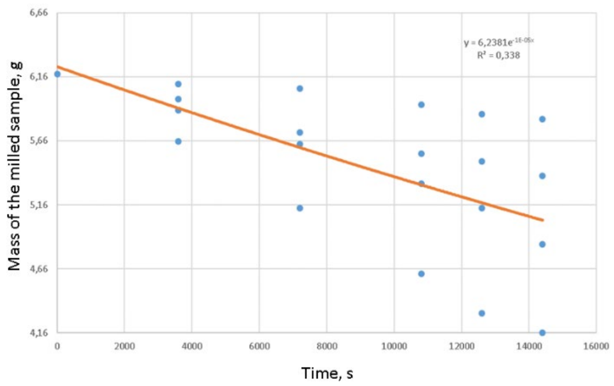


Fig. 5.4 Time variation of the average mass of the sample of milled dental material, in the working process

It is observed that both bodies (dental cutter and dental material), which interact (are in contact with relative movement) lose mass. The loss of mass over time has a variation after an exponential curve even if, in the prescribed working interval, due to the values of the parameters, their curvature is less visible / accentuated. Finally, introducing the other parameters, presented above, which describe the modeling of the wear phenomenon, in the form of mass loss, the solutions of the system / mathematical model of differential equations (5.8), become:

$$y(t;v,F) = y_0 e^{-\psi_0 v \cdot \frac{HVx}{HVy} \cdot \frac{F}{y_0 g}(t-t_0)}, \tag{5.14}$$

for the mass lost by the dental cutter, and:

$$x(t;v,F) = x_0 e^{\frac{\eta_0}{\psi_0} \cdot \left(\frac{HVy}{HVx} \cdot \frac{g}{F}\right)^2 \cdot y_0 [y(t)-y_0]}, \tag{5.15}$$

for the mass lost by the milled dental material; the initially set pressing force F is adjusted by placing the micrometer screw on the tray of the stand to advance the milled sample to the dental cutter (see paragraph 3.7, chapter 3).

For the mass lost by the dental cutter and the mass lost by the milled dental material, the efficiency ratio of the dental cutter e and the working speed of the dental cutter were also taken into account, by means of the rotation frequency, v and pressing force, F, as being the most important control parameters. The functions of the loss of mass of the milled dental material, respectively of the dental cutter, are defined in the form of the relation (5.9) which can be written in the form:

$$\delta x(t) = x_0 - x(t), \delta y(t) = y_0 - y(t), \tag{5.16}$$

and the efficiency ratio of the dental cutter:

$$e(t) = \frac{\delta x(t)}{\delta y(t)}, \; t > 0, \tag{5.17}$$

that is: the ratio between the lost (removed) dental material in grams (g) and / the lost (removed) dental cutter material in grams (g).

The graphical representation of the variation of the mass of material lost by the dental cutter and the mass of the milled dental material as a function of time, taking into account the functions of mass loss (5.16 and 5.15), can be seen in fig. 5.4, and the variation in time of the efficiency ratio e (t) between the loss of mass of the milled dental material and the loss of mass of the material of the dental cutter is represented in fig 5.5.

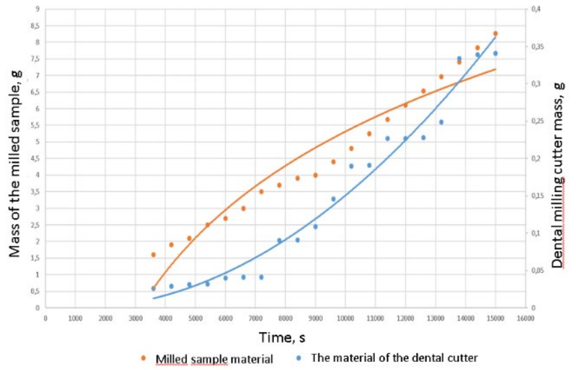


Fig. 5.5 Time variation of mass losses of milled dental material and of the experimentally measured dental cutter

Curves, with variation similar to that of fig. 5.5, obtained experimentally by measuring wear and periodic weighing depending on the established working time are also found in the works [8, 9, 15, 19].

In the literature, the search for efficient methods of measuring / expressing wear continues. In this paper we tried to express wear in terms of weight loss by weighing, but in the paper [20], which presents some of the author's experimental research, where wear was also expressed in geometric terms (changes in lengths, thicknesses or angles).

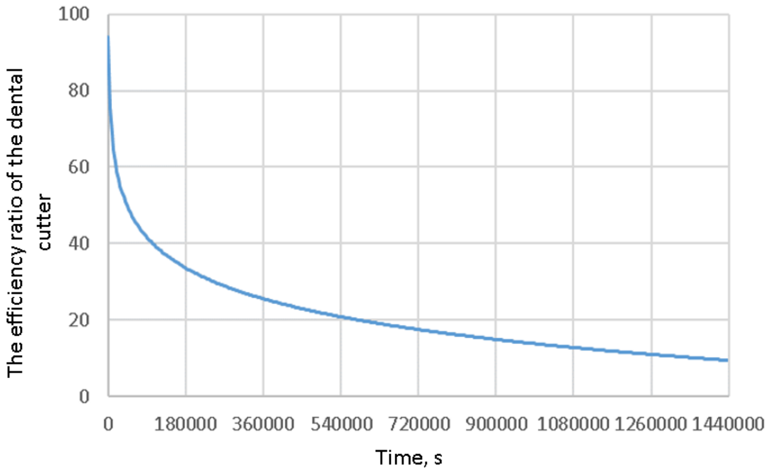


Fig. 5.6 Time variation of the efficiency ratio e (t) between the loss of mass of the milled dental material and the loss of mass of the material of the dental cutter

Based on the graphical representations of Fig. 5.5 and 5.6 it can be seen that the material, configuration and composition of the cutter material allows it to be efficient, which means that a small amount of lost dental cutter material removes more material from the milled dental material. However, this effect is visible for a much longer time of four hours of operation, after which the experimenter noticed the inefficiency of dental cutters. (see paragraph 4.8.4, tab.4.5, chapter 4). From this point of view, the model developed directly for the contact phenomenon with relative motion between the dental cutter and the milled dental material based on the “prey-predator" model, needs improvements, but they can bring complications in solving the system of equations of the mathematical model.

5.3 The effect of the modification of the constructive working parameters of the dental cutters on the dental materials

It is mentioned that the subject of research in this thesis is the dental cutter and the dental material that is processed with the cutter. For the dental cutter, it is interesting for the researches performed, its active part, also called the head of the dental cutter. Therefore, when we refer to the parameters of a dental cutter, we take into account the parameters of its active part. Thus, the constructive-functional parameters of the active part of the dental cutter are of a geometric, physical or chemical nature. The geometric parameters are: the shape of the surface of the active part of the cutter, on which the teeth or the basic surface of the teeth are anchored, the shape and dimensions of the teeth (height of the teeth, profile of the flanks, characteristic angles, etc.).

5.3.2 Influence of chemical concentration on material properties of the active part of the dental cutter

The physical parameters of the active part of the dental cutters are defined by the mass and its mechanical characteristics (hardness, limit stresses and specific deformation of the dental cutter material, etc.), and the chemical parameters are given by the composition of the dental cutter material (alloy). Some of the geometric, physical and chemical parameters were presented in chapter 4 of the doctoral thesis. (see fig.4.30, tab.4.2, tab.4.7)

The influence of the constructive-functional parameters of the active part of the dental cutters on the working process, refers to the mechanical properties of the material of their active part, more precisely to the way in which these properties are influenced by the chemical composition of the material. From the mechanical properties of the material of the active part of the tested dental cutter, we chose the Vickers hardness (HV), because it was studied and the results are presented in chapter 3 of the doctoral thesis. (sub-item 4.52, tab. 4.1)

During the experimental tests, for a number of three dental cutters of the same, the HV hardness of the material of their active part was measured and the chemical composition was determined by metallographic and chemical analysis (see table 4.1 and fig.4.30 in chapter 4). To illustrate the accuracy of the results obtained by the procedure used, these data were compared with the high-resolution experimental results in the literature [25].

The processing of data from [25], corresponding to an iron-based alloy, had to be done carefully because a standard approach with a linear and free-term regression, in addition to being unrealistic, induces certain errors (such as example decreased alloy hardness relative to Ni concentration). The expression of the Vickers hardness of the toothpaste material in relation to the concentrations of eleven chemical elements included (or identified by analysis) in the analysis list, in the case of standard linear regression is:

$$HV = 756.768 + 230.515\,C - 22.257\,Co - 13.647\,Cr - 278.144\,Mn + 16.989\,Mo - \\ - 2.935\,Ni + 1860\,P - 189.315\,Si - 257.982\,Ti - 82.348\,V - 9.718\,W \quad , \qquad (5.18)$$

in which: $C, Co, Cr, Mn, Mo, Ni, P, Si, Ti, V$ and W are the concentrations of the chemical components of the dental cutter alloy, and their coefficients represent the concentrations (in percentage weight) of the chemical components of the alloy, ie the eleven terms of the Vickers hardness function (HV).

The relation (5.18) is obtained by the least squares method from the data included in table 5.3. Table 5.3 contains data from the literature and is not the result of thesis research. The experimental results obtained in the thesis include only 8 elements: W, Fe, Cr, Mn, Co, Cu, Zn, Ni, according to the experimental plan. The relation (5.18) is elaborated in the thesis research to show that it is possible to estimate the hardness by knowing the concentrations of the alloying elements. The compositions in chap. IV and from [25] also have common elements but they also have differences: in the analyzes in chap. IV do not appear: C (element present in any steel), Mo, P, Si, Ti, V, instead in [25] does not appear Fe (basic element in any steel), Cu, Zn. Formula (5.8) gives a variant of further research not only for the ends of the milling cutters but also for any type of steel and other materials, more precisely the research of the possibility to express the hardness (or other mechanical or more generally physical properties of the alloys depending on the concentrations and properties of alloying components).

We observe from (5.18) that the Ni concentration coefficient is negative, which leads to the conclusion that increasing the Ni concentration would decrease the hardness of the alloy. However, according to Fig. 4.30 in Chapter IV, Ni is an element that increases hardness. Taking into account the above considerations and the calculations of the authors of the paper [25], the best linear regression with zero free term was obtained (see relation 5.19). This regression (5.19) is obtained using the least squares method with data from the same source [25], as for the HV hardness function (see relation (5.18)):

$$HV = 24323C - 312CO + 19CR - 336MN - 172Mo + 88Ni + 4710P - 624Si + 5888Ti + 32V + 104W \quad (5.19)$$

In the HV hardness function in (5.19), Ni has a positive concentration coefficient, so it confirms that alloying with Ni increases HV hardness. However, Co, which should also increase the hardness of the alloy, in both relation (5.18) and relation (5.19) has negative coefficients. Taking into account these aspects and the fact that the authors of the paper [25] have relations with all the coefficients of the concentrations of positive chemical elements, we can find a functional that is minimized by the type of relation (5.20) with the positive coefficients, minimizing the function:

$$\Psi(c_0, c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_9, c_{10}) = \sum_{k=1}^{N}(c_0C_k + c_1Co_k + c_2Cr_k + c_3Mn_k + c_4Mo_k + c_5Ni_k + c_6P_k + c_7Si_k + c_8Ti_k + c_9V_k + c_{10}W_k - HV_k)^2 \quad (5.20)$$

where: k - is the index that identifies the set of experimental data, ie there are N analyzes that give a set of concentrations of each alloying element, each set having an index k = 1, ..., N, provided that:

$$c_k \geq 0, k = 0,...,10, \quad (5.21)$$

where: c_k are the coefficients of the concentrations of the chemical components.

Condition (5.21) is a functional restriction (5.20) to avoid modeling contradictions such as negative coefficients of some alloying elements. Without the restriction in (5.21) of the positive coefficients there will be a lower hardness calculation accuracy with relation (5.22) than with relations (5.18) and (5.19). The HV hardness function is obtained, of the form:

$$HV = 744.971Cx + 13.213Crx + 114.918Mnx + 17.254Nix + 100.171Vx + 15.976Wx, \quad (5.22)$$

where: *Cx, ..., Wx,* are the arguments of the function *HV=HV(Cx,Crx, Mnx,..., Wx)*, arguments or independent variables in relation (5.22), concentrations of alloying elements, limited for physical reasons to values known to the manufacturer. Conformable (5.22), *N =10.*

All the chemical elements in the HV hardness equation (relation 5.22), having the coefficients of the concentrations of the positive component chemical elements, increase the HV hardness function, so the HV hardness increases.

For further clarification, let us compare the correlations between the vector (column) of HV hardness and the vectors (columns) of the elements in table 4 of the paper [25]. The comparison is presented numerically and graphically in fig. 5.6.

Relationships (5.18) and (5.19) also have negative coefficients, in agreement with the correlation coefficients in fig. 5.7 and are more accurate in relation to the experimental data, relation (5.22) solves this contradiction, but with less precision than relations (5.18) and (5.19).

It is observed that the chemical elements best correlated with hardness are, in order: C, Mo, V, W and Cr. It is generally known that the hardness of iron-based alloys increases linearly with the carbon concentration [34].

Among the chemical alloying elements for increasing the hardness in the list given in [34], in correlation with table 4 in the paper [25], C, Mo, Cr and V are highlighted. Nickel remains ignored in the alloys in the paper [25], in that regarding its role in increasing hardness. It is possible to introduce chemical alloying elements to improve properties other than hardness.

The materials used for the manufacture of the active part of the dental cutters are mentioned in the standards mentioned in Chapter I (Annex 1) of the doctoral thesis.

5.4 Reliability and durability of dental cutters

Rigorous studies of reliability and durability are quite few in the literature, [1]. Reliability is a quality characteristic that includes the ability to use over time (lifetime / durability) of a product, device or system whose quantitative estimation is based on the reliability indicators [21] presented below:

a) the reliability function;
b) malfunction function (distribution function), or unreliability;
c) frequency function (distribution density);
d) average time (average duration) of good operation;
e) dispersion of the distribution;
f) quantum of operating time;
g) intensity (rate) of failure.

Reliability and durability studies involve a large number of experimental tests, performed on a batch of objects, in real time operation. For each object, the time of decommissioning or service life is noted. For systems where it is possible to restore working capacity, it also means timing the repair, respectively the new working time, etc. The authors of the paper [1] estimate that "in the processing process, in order to avoid defects and their consequences, tools are often replaced long before the end of their useful life. Usually, only 50-80% of the expected life of the tool This is particularly the case for production systems, where the physical strength of the working process is critical. there are studies that suggest that these tool costs may be much higher "[11].

The first three reliability indicators were taken into account, because they are the ones that lead us to conclusive and significant results for the main objective of the doctoral thesis.

a) Reliability function, denoted by *R (t)* - indicator that expresses trouble-free operation within a set time period (t).

Qualitatively, the reliability of a system is defined as its ability to correctly perform the functions provided / established and to function perfectly within a set time frame, under specified operating / operating conditions. Quantitatively, the reliability of a system is the probability of operation expected / specified at a given level, over a certain period of time, under specified operating / operating conditions. According to this definition the mathematical expression will be:

$$p(t) = Prob\,(t \geq td) = R(t), td \geq 0, \qquad (5.23)$$

where:

$p(t)$ represents the probability of correct operation, ie reliability;

t represents the operating time;

t_d is the specified limit of good service life (correct operation), or is the operating time until the first system malfunction. Symbolically we can write $\{t \geq td\}$, and therefore the relation (5.23) is justified.

Given the properties of probabilities, it follows that for $t = 0$, $p(t) = R(t) = 1$, for $t \to \infty$, $p(t) = R(t) = 0$ and function $R(t) = p(t)$ it is a decreasing function. The probabilistic expression of reliability argues that the occurrence of a malfunction during operation is not accurately established, but can be determined in the form of the probability to which a confidence level can be associated.

b) Failure function (distribution), *F (t)* - indicator that represents the probability of failure of the designed system to operate for a set period of time (t_d). The mathematical expression of this indicator is: $F(t) = Prob\ (td \ \leq \ t),$ (5.24)
and the relation between the functions R and F is the following:

$$F(t) = 1 - R(t)(t \geq 0), \tag{5.25}$$

The reliability function, *R (t)* is used to determine the reliability of the system, ie the probability that the system will operate at time t; the distribution function *F (t)* is used to determine the probability of system failure in the time interval [0, t). That is why the distribution function *F (t)* is also called the system failure or unreliability function.

c) Frequency function, *f (t)* - expresses the relative frequency of failures in an elementary time interval dt, or the probability or distribution density of the time variable, t (density of distribution of operating time).

We assume that the function *F (t)* is differentiable at any point t ≥ 0 and its derivative, we denote by *f (t)*, that is:

$$f(t) = F^{'}(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt}, (t \geq 0), \tag{5.26}$$

The function *f (t)* is assumed to be continuous on its domain of definition, [0, ∞) and has the following properties:

$$f(t) \geq 0, \forall t \geq 0, \tag{5.27}$$

and

$$\int_0^{\infty} f(t)dt = 1, \tag{5.28}$$

Under these conditions, there are the following links between the reliability function, the failure function and the frequency function:

$$F(t) = \int_0^{\infty} f(t)dt; R(t) = 1 - \int_0^{\infty} f(t)dt = \int_0^{\infty} f(t)dt, (t \geq 0), \tag{5.29}$$

It follows from relations (5.25) and (5.26) that the derivative of the reliability function, *R (t)*, is: $R^{'}(t) = -f(t),$ (5.30)

d) Average service life (average duration), *M (t)* - is the indicator that expresses the average value of the operating time or the average number of operating cycles until failure, is the case of irreparable machine elements, or until the first failure , the case of repairable car parts.

This average operating time represents the average of the times (durations) of good functioning for a statistical population that was taken into account. Assuming the frequency function or operating time distribution density, *f (t)* as a continuous function (5.31):

$$M(t) = \int_0^{\infty} R(t) = \int_0^{\infty} tf(t)dt, \tag{5.31}$$

e) Distribution dispersion, D2 (t) - is an indicator that represents the deviation of the values of the times of good functioning from their arithmetic mean, expressed in (hours2) or (number of cycles of operation2), and mathematically is defined by the relation:

$$D^2(t) = \int_0^{\infty} \left(t - M(t)\right)^2 f(t)dt, \tag{5.32}$$

The mean square deviation expresses the degree of scattering of the times of good functioning, given by the relation:

$$\sigma = D(t) = \sqrt{D^2(t)}, \tag{5.33}$$

f) Operating time quantile, tα - is another reliability indicator, independent of time, defined as the root of the equation:

$$F(t_a) = a\ , \qquad (5.34)$$

where. α is defined percentile with values from 0.01 ... 0.99.

This indicator expresses the time in which a system or a component of it works but a certain probability (1 - F), F - being the failure function. For practical interests, tα is chosen 0.10, 0.50 and 0.90, and the corresponding times will be t10, t50, respectively t90 [26].

g) Intensity (rate) of failure - expresses the probability that a coupling / pair of friction, a machine element, etc., that operated without failures until time t, this to be possible in the period of time, immediately following,*(t, t + Δt)*, (*Δt* very small):

$$h(t) = \lim_{\Delta t \to 0} \frac{F(\Delta t)}{\Delta t} = \frac{dF(t)}{R(t)} = \frac{f(t)}{R(t)}, R(t) \neq 0, \qquad (5.35)$$

For many cases encountered in the practice of friction torques / pairs, machine elements and mechanical transmissions, as a system, the intensity of failures, *h (t)* is presented as in Fig.5.8, also known as the curve "bathtub.

Application of the reliability function for the active part (samples) of the dental cutters

The active part of the dental cutters is the component without automatic restoration, which once worn, the cutter is no longer repaired, but replaced (replaced). Considering the experimental results, and, in addition, the consultations of the users of the dental cutters, who use / consume a lot of dental cutters, it results that:

- the active part of dental cutters operates with a very low probability of failure up to a time, t_{min}, after which the probability of failure increases rapidly up to a time, t_{max}, after which practically no cutter is generally usable;

- the period of decommissioning of the active part of a dental cutter, t_{max} - t_{min}, is due to the small differences between the manufacturing characteristics of the same type of active part (slightly different masses, angles, etc.). These differences ultimately have implications for lifespan, as seen in the calculation of sustainability, subchapter 5.2. The increase in the probability of failure [t_{min}, t_{max}] is all the greater the greater the differences between the active parts of the same type, even in the same set of products.

With these two observations and using the definitions of the functions of "hat" and "bump", it is proposed for the operation of dental cutters a reliability function having the expression, [10; 32]:

$$R(t) = \begin{cases} \exp\left(\frac{1}{t_{\max}^{2n}}\right) \cdot \exp\left(\frac{1}{t^{2n} - t_{\max}^{2n}}\right), & 0 \le t \le t_{\max} \\ 0, \quad t > t_{\max} \end{cases}, \qquad (5.36)$$

where: t_{max} is the time after which it is experimentally found that the active parts of the milling cutters of the same brand and type have failed, and n is a parameter that can be chosen so that the time at which the exponential increase in probability begins failure, t_{min}, to be best estimated.

In this case, a satisfactory estimate is obtained for n = 0.75. Under these conditions, the variation of the reliability function over time (from relation (5.36)) is represented graphically in fig. 5.8, for dental cutters type F1-5 whose characteristics are given in table 5.2, at the milling speed of 7000 rpm. The times t_{min} = 10,265 hours, respectively t_{max} = 12,613 hours were estimated according to table 5.2, from experimental determinations.

Figures 5.9 and 5.10 show graphically the failure and frequency functions corresponding to the reliability function, *R (t)*, in relation (5.36).

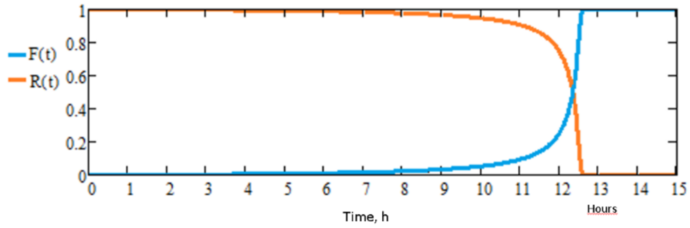


Fig. 5.9 Graph of the failure function, *F (t)*, and the reliability function, *R (t)*, for the active parts of the tested and symbolized dental cutters Fn.m

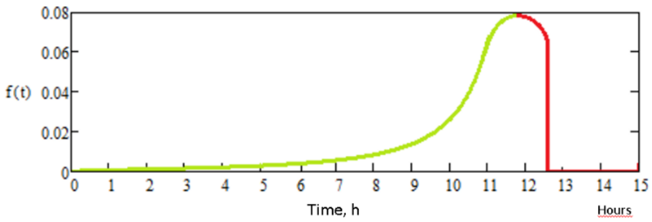


Fig. 5.10 Frequency function graph, *f (t)*, for dental and symbolized milling cutters Fn.m

It is observed that the reliability function is monotonically decreasing, with values in the range [0, 1] and when time tends to infinity ($t \to \infty$), ***R (t)*** is canceled (even for finite values, ie t_{max}, in our case,$R(0)) = 1$ and when $t \to \infty$), $R(t) = 0$). The failure function, *F (t)* is increasing, with values in the range [0, 1], $F(0) = 0$ and when $t \to \infty$), $F(t) = 1$ and the frequency function, *f (t)* verifies the relation (5.28).

5.4.3 Calculation of the characteristic sizes of the reliability of dental cutters

The reliability of dental milling cutters can also be highlighted with the help of the characteristic numerical quantities attached to the variable time t, operating time until the first failure. These characteristic values are: mean value, dispersion, mean square deviation and operating time quantile.

The average value, *M (t)* of the failure-free operating time (without complete decommissioning (operation)) is according to relation (5.31), in correlation with the values in table 5.2. By numerical integration of the function, the value of the operating time without failure was obtained in working conditions with a speed of 7000 rpm:

$$M(t) = \int_0^\infty R(t)dt \; sau \; M(t) = \int_0^\infty tf(t)dt = 11.947 \text{ , ore} \quad (5.37)$$

The system (the active part of the dental cutter) being without reconditioning (renewal), then *M (t)* represents the average of the good operation time of the system until the unique failure of the system. The average time without failure (average of the good operation time) of the system, ie the average value of the time variable t, can be expressed either by means of the reliability function *R (t)* or by means of the frequency function *f (t)* (see relation (5.37).

There are also defined other numerical quantities characteristic of reliability, useful for the system (the active part of the dental cutter), namely: median and mode, defined in chapter 2, subchapter ... Thus, the median of the variable time, t, is the median failure time, denoted by t_{med} , and is [5, 29]:

$$R(t_{med}) = 0{,}5, \quad (5.38)$$

The line segment t = ⟦t⟧ _med shows the symmetrical distribution of the faults by dividing the area of the graph as a function of frequency *f (t)* and the axis O_t in equal parts (fig. 5.11), which shows that half of the faults occur before t_{med}, and the rest after t_{med}. If the distribution of failures is asymmetric, it is preferable to use the average value to the detriment of the median. For the considered system, t_{med} = 12,349 hours, which is presented in the graph in figure 5.7.

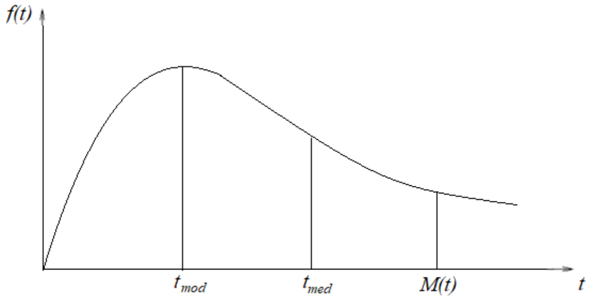


Fig. 5.11 Numerical characteristics of random variables, *t*

The modulus of the random variable, *T*, is the most likely failure time to be observed. It is denoted by, t_{mod} and defined by the function:

$$f(t_{\text{mod}}) = \max_{0 \le t \le \infty} f(t), \tag{5.39}$$

which, in the case of the active part of the dental cutter symbolized by Fn.m, has the value: t_{mod} = 12.23 hours being the abscissa of the maximum point of the function defined by the relation (5.39).

The dispersion of the random variable, *T,* or the dispersion of the distribution, D^2 *(T*) is defined by the relation (5.32) and is obtained:

$$D^2(T) = \int_0^{\infty}\left(t - M(T)\right)^2 f(t)dt => D^2(T) = 1.498, \text{ ore} \tag{5.40}$$

The quadratic mean deviation, σ of the random variable, T, is the characteristic numerical quantity that can be used, often, instead of the dispersion and has the form given in the relation (5.33), which by replacement, we obtain:

$$\sigma = D(T) = \sqrt{D^2(T)} \Rightarrow \sigma = 1.224 \quad \text{ore}, \tag{5.41}$$

$D^2(T)$ and *D(T)* by their values they show the degree of uniformity of the performances of the systems (here, dental cutters) from the point of view of reliability. For well-developed technical systems, the values of the two are very low.

In this case, *$D^2(T)$,* and *D(T)*, shows the degree of uniformity of the set of dental cutters tested.

Another important reliability indicator is the operating time quantile, t*α*, resulting from equation (5.34). That is, t*α*¸ and defined as the root of the equation:

$$F(t) = \int_0^t f(t)dt,$$
$$F(t_\alpha) = \alpha => t_\alpha = 12.572, \text{ ore} \tag{5.42}$$

where: *α* is defined percentile.

By numerical calculation, for *α* = 0.99, t_α = 12,572 hours was obtained (at 7000 rpm).

The value of t_α is interpreted in reliability theory as a guarantee time, ie the time in which the proportion of defective elements in a given community does not exceed the initially established value *α* [5].

An important role in reliability theory is also the function that measures the instantaneous risk of failure (intensity (rate) of failure), *h (t)*, or hazard, defined as the limit of the failure rate in the range *[t, t + Δt], Δt > 0* very small [5]. After elementary processing (see relation (5.35)) the following simplified expression of this function is obtained:

$$h(t) = \frac{f(t)}{R(t)}, \quad R(t) \neq 0, \tag{5.43}$$

The graph of the instantaneous risk of failure function, *h (t)*, for the Fn.m symbolized dental cutters tested experimentally (see chapter IV, table 4.5) in the thesis is shown in fig. 5.12.

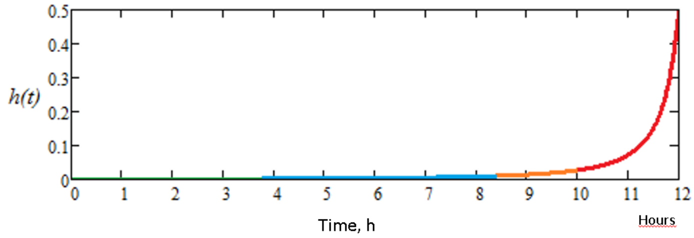


Fig. 5.12 Graphical representation of the instantaneous risk of failure function *h (t)*, for the batch of symbolized cutters Fn.m

In fig. 5.12 it is observed that for 11 hours the instantaneous risk of failure is below 10%. In the 12th hour of operation, the risk of failure (which in the case of the active part of the dental cutter means decommissioning) increases approximately exponentially, ie after 11 hours of operation it is normal to replace the dental cutter.

It is observed that the function *h (t)*, which measures the instantaneous risk of failure has an evolution that we can divide into four areas:

- the first zone, when t Є (0, 4) hours, there is no risk of failure and *h (t)* has a linear variation, close to zero;

- the second zone, when t Є (4, 8) hours, there are minimal (very low) chances of risk of failure, although *h (t)* has an all-linear variation with a very small slope;

- the third area, when t Є (8, 10) hours, starts to increase *h (t)*, has a curvilinear variation, so the wear phenomenon becomes visible and the risk of failure is increasing;

- the fourth zone, when t Є (10, 12) hours, *h (t)*, increases suddenly, after an exponential curve and the risk of failure is very high.

The researched dental cutters can operate without major risk of failure up to 10 hours, which is very close to those calculated analytically based on experimental results, which confirms the veracity of experimental results and the correlation between analytical calculation and experimental test results.

Based on the experimental results presented in Table 4.5 of Chapter IV, the mass lost by wear of the studied dental cutters, which is the researched feature, except for the influence of systematic factors, with two limit values (lower and upper), each value having a number of repetitions, so its own frequency.

The distribution of values (with their frequency) between the limit values of the range can be represented by a distribution law.

As the factors that determine the dispersion of the effective dimensions (masses lost by wear) are of the same order, in large numbers, independent, and accidental, then the law of distribution of the mass lost by actual wear, as a random variable (X - mass lost by wear, $X < x$ given and corresponds to a probability p), is the normal law of distribution (Gaussian).

The normal distribution or Gaussian distribution, representing the distribution density, the frequency function or the probability distribution density (probability density) f (x), is closest to the form of a normal distribution function (for blue and black curves):

$$f(x) = y = \frac{1}{1.22\sqrt{2\pi}} e^{-\frac{(x-11.95)^2}{3}}, \tag{5.44}$$

and for the (right) red curve (representing the data set that compares with those that led to the blue and black curves), a first degree polynomial function:

$$f(x) = y = x + 4e^{-15}. \tag{5.45}$$

which has the shape of fig. 5.13 (bell shape, where the variation of the function can be seen $f(x) = y$) and represents the probability density function curve, being slightly asymmetric (to the right, which can be explained by the fact that the mass lost by wear of the dental milling cutters is measured after use, ie close to decommissioning) to the axis corresponding to the grouping center (around 4.63) of the deviations for the frequency of distribution of the results after 100 measurements (blue and black curves), but with different distribution frequencies, observable and shown in Annex 3.

Considering the system of axes, in which the axis of the y = f (x) coordinates coincides with the raised line in the center of the deviation grouping (4.63), and the top of the Gaussian distribution curves is positioned to the right (slightly inclined to the right, see Fig. 5.13), which explains the above.

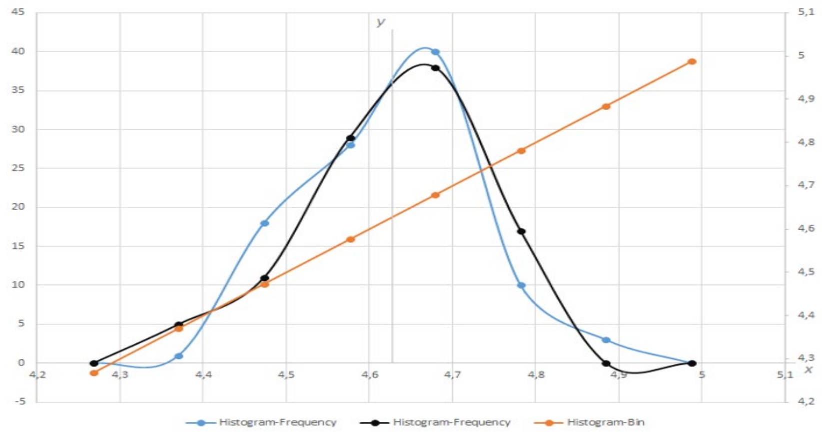


Fig. 5.13. Probability graph for normal distribution law (Gauss)

Two inflection points are observed on the probability density function curve, of abscissa 4.58 and 4.78, interval, where the surface area under the curve represents approximately 58.33% of the total surface area (ie, shows where the values of the random variable are most distributed (mass lost by wear by dental cutters $X < x$)). The curves tend asymptotically to the abscissa axis and have a maximum of approximately, x = 5.03 (blue curve) and 4.98 for x = 4.67, the reliability obtained being approximately 97.42%, so a very good reliability. If other characteristics were not taken into account, which were not taken into account, the total reliability will fall below 90%.

In the interval (4.38, 4.88) the surface between the curves and the abscissa axis is about 97.42% of the total surface, so that the intervals (-∞, 4.38) and (4.88, + ∞) can be practically neglected. So, the scattering interval is 0.50 (from 4.38 to 4.88), and the limit deviations have the values (± 0.25), compared to the center of the group, respectively the confidence interval is (4.38, 4.88) and the critical one is the interval (-∞, 4.38) U (4.88, + ∞).

Therefore, the values of the mass lost by wear have a Gaussian distribution and the frequency function or probability density is a function of normal distribution or Gaussian distribution (blue and black curves).

CHAPTER VI
PERSONAL CONTRIBUTIONS AND FINAL CONCLUSIONS

6.1 General considerations

All dental instruments are manufactured in accordance with EN ISO-Standard 6360. To achieve compliance, the International Organization for Standardization (ISO) has defined a standard description of rotary instruments used in dental technology. Each instrument is encoded with a separate ISO code number. This code consists of 15 numbers that are arranged in groups and simultaneously contain the description of the instrument

Quality, workmanship, safety of use for operators and patients, corrosion, strength, are just a few characteristics that should be taken into account when designing dental appliances and cutters.

The processes that take place by friction on the contact surfaces and in the surface layers, respectively in the micro volumes of the roughnesses in contact are of different nature and depend on a series of mechanical, physical, chemical, geometric and metallurgical factors.

The existence of different types of wear shows that the detachment of a particle of material, in most cases, requires several passes, fatigue depends on the nature of the particle.

The melting temperature and the atomic volume, in terms of wear resistance, can also be considered as indicators of material properties.

From the above it results that friction is a complex phenomenon characterized by energy consumption and material losses (wear) and is explained by the action of several components whose weights depend on the concrete elements of the friction bodies (surface topography by different parameters, physical properties and mechanics of the materials involved, speed, the environment between the surfaces in contact, etc.). Dominant are the mechanical and molecular components (due to the adhesion phenomenon).

The process of removing dental material with the help of dental cutters is a complex phenomenon, similar to friction and wear, or even chipping of materials.

The analysis of this phenomenon was performed experimentally and validated by statistical-mathematical modeling based on experimental results obtained from complex research.

The statistical-mathematical modeling allowed the establishment of the relations between the input, output parameters and the control parameters of the modeled phenomenon.

The stability, veracity and accuracy of the model used is influenced by the number of experimental data and the parameters involved in the process / phenomenon.

The working process of the dental cutters being a complex one, many of the basic parameters of the process could be established and quantified only after the statistical-mathematical modeling of the phenomenon, respectively the parameters and factors acting on the process, imposed the approach of experimental research by integrating fields. interdisciplinary.

From the metallographic analysis of the material of the dental milling cutter, no material gaps were found following the sanding process, even if oxides were found in the material as inclusions, but of very small dimensions.

A fine granular structure of the material of dental cutters and similar was noticed for all the researched dental cutters.

The samples of material taken from the two categories of dental cutters studied have increased hardness values (over 280 HV) and a very high resistance to compression stress (over 900 MPa), the hardness increasing to the marginal area of the active part of the cutters by about 28 , 70%, which can also be seen in finite element modeling.

Both the Vickers hardness values and the breaking strength are higher in the marginal area and lower in the middle, with the difference that the breaking strength is higher when moving from the middle to the edge area.

This is desirable, because it gives the dental cutter a good tribological behavior (minimal friction and wear), so an extension of the service life, and the lower values in the middle ensure a toughness of the dental cutter.

The wear behavior was analyzed by the mass lost by the active part of the dental cutters (dental), in the process of operation, after certain periods of time, depending on working time, speed, feed and properties of the materials of the tested dental cutters.

The statistical-mathematical processing of experimental data was performed by polynomial interpolation resulting in functions that represent the variation of the parameters characteristic of the wear process (m_{fw} - mass lost through wear and m_m - mass of processed dental material), depending on the parameters modified during experimental research (ω - rotational speed, F - normal pressing force, p - pressure in the contact area, H_{fm} - hardness of the dental cutter material, H_m - hardness of the processed dental material)

6.2 Personal contributions

Some complex problems encountered in the dental field were solved by metallographic and chemical analysis of the material of the tooth cutters tested and of the dental material processed during the experiments (Ni-Cr alloy), respectively the determination of the mechanical properties of the active part of the researched tooth cutters.

Using the finite element method it was possible to establish the stresses and strains in the material structure of the experienced milling cutters, the critical points where they appear, to take into account in optimizing and increasing their life, improving the mechanical properties of materials.

From the spectrophotometric analysis with the X-ray analyzer it was found the presence of a large number of chemical elements (W, Fe, Cr, Ni, Co, Mn, Cu, Zn) in the composition of the material of dental cutters, n / ω.

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

It was found that the maximum wear of the researched dental cutters is when the functional parameters of the active part of the dental cutters have changed, respectively the angle of placement, clearance, sharpening, the area of the top circle.

The polynomial interpolation functions allowed the determination of some characteristic points, which represent the (extreme) wear values of the active part of the dental cutters.

The two independent variables of the experimental program (operating time, t and speed of the tooth cutter, n / ω can be expressed by one, ie "angular friction distance, θ (circumferential friction length)".

This proves that the loss of material occurs over time by rubbing and cutting (detaching / removing) material at the contact of the milling cutter - dental material, after traveling an angular distance (circular friction length) in the process of operation, which have the effect Wear.

The idea of modeling the interaction (contact with relative motion), dental cutter-processed dental material, starting from the “prey-predator” model is, in principle, successful for short periods of time, simulation.

The behavior from which the asymptotic phenomena are noticeable, however, is high, in relation to the experimentally established working time, at which the dental cutter becomes inefficient.

The researched dental cutters can operate without major risk of failure up to 10 hours, which is very close to those calculated analytically based on experimental results, which confirms the veracity of experimental results and the correlation between analytical calculation and experimental test results.

6.3 Final conclusions

The model does not lead to the complete solution of the problem, without experimental information, and if the experimental information is used, as was done in this case, the model becomes an approximate one because the experiments were performed on a single type of dental cutter.

The polynomial interpolation of the experimental data led to functions to describe the phenomenon of wear of the milling cutters during the experiments, because it approximates well the dependent parameters of the experimental program.

The polynomial interpolation functions allowed to determine some characteristic points, which represent the limit values (extreme) of wear of the active part of the dental cutters.

The working process of the milling cutters being a complex one, many of the basic parameters of the working process (speed, time, contact force, temperature, respectively the limit amount of mass lost by wear by the dental milling cutter in operation) could be established and quantified only after the statistical-mathematical modeling of the phenomenon.

The wear behavior was analyzed by the mass lost by the active part of the dental cutters, in the operation process, and the distribution of the experimental results was a normal Gaussian one based on the Gaussian function.

Also, by statistical-mathematical modeling of the wear process using polynomial interpolation of experimental data obtained in the working process of dental cutters can lead to practical applications, such as criteria for replacing worn dental cutters.

The problems presented, analyzed and experienced regarding the dental cutters had practical purposes (optimization or improvement of the operating regimes, possibly the materials from which they are built, the life of the dental cutters, etc.

6.4 Future research directions

It is proposed, for a more complete solution of the problem of wear of dental cutters, to obtain much more experimental information on other types of dental cutters, respectively to extend the finite element method on other characteristics / properties.

In order to obtain better results in modeling the phenomenon of interaction (contact with relative movement) of the dental cutter with the dental material to be processed, the introduction of a function or coefficients to express the tooth efficiency of the active part of the dental cutters is a necessity.

This model opens a research direction, possibly very profitable, in which the “prey-predator” model is applied to cutting phenomena, erosion, friction, etc.

In order to obtain the best possible results, qualitatively and quantitatively, it is necessary to introduce other functions in the system of “prey-predator” equations, which will model the aggression of the predator.

Extension of interaction modeling (contact with relative motion), dental cutter-milled dental material starting from the “prey-predator” model and for longer simulation time periods.

Based on other experimental results and time variation curves, on other types of dental cutters to find the shape of the reliability function and to highlight the normal (Gaussian) distribution in this case.

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English	C1	Experienced user	C1	Experienced user	C1	Experienced user	C1	Experienced user	C1	Experienced user
French	B2	independent user	B2	independent user	B2	independent user	B2	independent user	B2	independent user
	(*) Level of the Common European Framework of Reference for Languages									
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