UNIVERSITY **POLITEHNICA** OF BUCHAREST

Faculty of Mechanical Engineering and Mechatronics
Department of Mechatronics and Precision Mechanics

PhD THESIS SUMMARY

Cercetări privind realizarea protezelor dentare prin depuneri selective cu laser și prin alte tehnologii aditive

Research on the realization of dental prostheses by selective laser deposition and other additive technologies

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Bucharest
2021

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INTRODUCTION AND OBJECTIVES OF THE DOCTORAL THESIS

In recent years, additive technologies are occupying an increasingly important place in the medical field and especially in dentistry. 3D printing is applied in many areas of health and this has significantly improved the overall health of patients in need of urgent and quality medical services. The importance and necessity of dental prostheses is due not only to aesthetic problems, but also due to inevitable and irreversible pathological changes in the tissue structure of the dento-maxillary apparatus generated by the absence or degradation of teeth, but also the features necessary for the functional characteristics of the masticatory apparatus, which directly influences the health of the body at the systemic level. In addition, the topicality of dental prosthetics is not limited to the medical aspect. The partial absence of teeth or other dental deficiencies prodused by various causes affects the social status and general psycho-emotional state of the patient. Therefore, the immediate replacement and restoration of missing dental tissues becomes of vital importance in this case for regaining comfort, solving medical and social problems and thus for increasing the quality of life.

At present, there are several classical and computerized technological variants for tooth replacement, each of which has its advantages and limitations, and the success over time of dental prosthetic restorations from a technical and medical point of view depends on several factors, which must be analyzed with attention, including the properties and physical and mechanical characteristics of dental prostheses or the degree of biocompatibility of the material used. Also, ideally, given the individual characteristics of the dental situation for each patient, the prostheses realized should meet the anatomical and physiological requirements by precision of execution and adequate geometry, but at the same time their execution duration and the effects of patient discomfort during the clinical stages before prosthesis should be as low as possible.

Recently, the methods of additive manufacturing in dental applications are enjoying a growing interest, both for making dentures or dental crowns, and for creating dental models for future prosthetic work. Given the importance of immediate prosthesis in case of dental deficiencies and all those mentioned above, in doctoral thesis I focused mainly on the study, realization, characterization and some analysis and optimization solutions for dental prostheses realized by selective laser deposition, as well as for dental models made by other additive technologies that can have multiple applications in the field of dental prosthetics, including the role of prototype/model for future restoration, and among the main objectives to be achieved in the thesis are:

- The study of dental tissues from an anatomical point of view and the problems related to the particularities of dental prosthetics;
- Analysis of the current state of the art of making dental prostheses and conducting a comparative study of them to identify the advantages and disadvantages for several considerations for each method of obtaining dental prostheses;
- Carrying out a study on the biomaterials used in dental prosthetics and their essential characteristics;
- Elaboration of an original method of comparative analysis of dental prosthetic biomaterials taking into account their essential characteristics and properties, following which it will be easier to choose the appropriate material for each patient, depending on several parameters and factors;
- Identification of technologies and materials used in additive manufacturing with possible applications in the field of dental prosthetics and their post-processing procedures, as well as proposing other applications of additive technologies in medicine and other fields;
- Realization of dental prostheses and dental prosthetic models through several additive technologies - selective laser deposition, thermoplastic extrusion, vat

photopolymerization, but also through modern subtractive CAD-CAM technologies, using different equipment, materials, software systems and characteristics/conditions of printing, while comparatively characterizing the elements obtained by additive technologies and identifying solutions for their analysis and optimization for dental prosthetic applications;
- Using the numerical analysis by the finite element method to simulate dental structures obtained by personalized digital intraoral scanning;
- Mathematical modeling of the selective laser melting process and determination of the influence of some important process parameters on the thermal characteristics of some dental biometals during manufacturing;
- Evaluation of mechanical characteristics for dental prosthetic models made by different additive technologies, from different materials and equipment, by subjecting to some mechanical loads, processing and comparing the experimental data obtained;
- Experimental identification of the most suitable materials for making dental prosthetic models in terms of wear resistance;
- Carrying out experimental researches on the dimensional accuracy of dental models made by additive technologies depending on the material and equipment used, identifying possible causes of dimensional errors by using modern measurement systems;
- Examination of surface condition and chemical composition for dental prostheses made by selective laser melting at different stages of post-processing using advanced optical methods and instruments;
- Experimental determination of the hardness of polished dental prosthesis made by selective laser melting and comparison of the results obtained with the hardness values for the same alloy, but made by classical technologies;
- Establishing perspectives for the development of researches on dental prostheses made by selective laser melting and prosthetic dental models made by additive technologies.

In order to achieve the objectives set for the doctoral thesis and to carry out several original studies and research, advanced and varied equipment, methods and programs were used for the execution, analysis and characterization of dental prostheses and dental prosthetic models.

The doctoral studies was partially supported by the European Social Fund from the Sectoral Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Scholarships for entrepreneurial education among doctoral students and postdoctoral researchers (Be Antreprenor!)", Contract no. 51680/09.07.2019 - SMIS code: 124539.

SYNTHESIS OF THE CONTENT OF THE DOCTORAL THESIS

The PhD thesis includes a preface and an introduction, and then it is structured in seven chapters, as presented in the table of contents and ends with conclusions, bibliography and appendix. The thesis has a total of **264** pages and **206** bibliographical references. Some of the research developed in the thesis were disseminated by participating in international scientific events and/or publishing scientific papers with the results of research in specialized journals, indexed ISI and/or BDI.

Chapter 1 entitled **"Problems regarding dental anatomy and prosthetics"** presents the main histological and geometric elements of teeth, the classification and role of teeth, as well as the main dental diseases that lead to the need for prosthesis. This chapter also presents the classification of dental prostheses from several points of view: depending on mobility, depending on the aesthetic appearance (Fig. 1), the mode of aggregation to dental tissues and the material used (Fig. 2) and depending on the technology of execution of the prostheses [4] [6] [10] [11] [15] [31].

Fig. 1. Dental prostheses studied according to the aesthetic aspect

Fig. 2. Dental prostheses according to the material and the aggregation mode to the dental tissues

Chapter 2 entitled **"Current stage regarding the technologies for obtaining dental prostheses"** presents the main technologies for the execution of dental prostheses, highlighting the advantages, disadvantages and the procedures for realizing dental prostheses are studied comparatively. Following the research of the current state of the art of realizing dental prostheses, it is concluded that there is a wide range of technologies and techniques for replacing dental tissues. Every technology for realizing dental prostheses has its advantages and disadvantages, and the proper choice of it is essential in order to have an optimal utility and viability of prosthetic elements. Casting and techniques of obtaining by plastic deformation of metals are the most suitable variants from a financial point of view of tooth restoration, but they are outdated methods, with many disadvantages. In addition, the range of materials is limited. A very important role in the manufacture of dental prostheses has the choice of material, which must be compatible with human tissues, to avoid rejection of the prosthesis by the patient's body. The manufacturing technologies with the best performances of the realized dental prostheses are without a doubt the computerized CAD/CAM technologies (milling CAD-CAM and selective laser melting), which eliminate a series of deficiencies. Among the computerized technologies lately, the additive technologies are gaining more and more interest, namely the selective laser sintering/melting techniques (Fig. 3). These manufacturing methods provide an efficient and fast method for designing and obtaining biocompatible metal frames for complex dental prostheses. SLS/SLM technologies compensates the disadvantages of milling technology - excellent manufacturing accuracy and no burr edges. In addition, these are some adding material technologies. Unused material can be reused in the following processes, which makes these technologies much more cost-effective than milling [31] [51] [55] [56] [57].

Fig. 3. NiCr dental prostheses made by selective laser deposition in raw/finished state

In **Chapter 3 "Biomaterials used for obtaining dental prostheses"** I presented the main classes of biomaterials for realizing dental prostheses, as well as their essential properties and characteristics [58] [59] [61] [66] [70]. Also, in this chapter I have developed an original method of comparative analysis of biomaterials used to realize dental prostheses depending on the main features and essential factors, with which it is easier to choose the appropriate material for each individual patient. Following the study conducted in this chapter, it can be concluded that no biomaterial used in dental prosthetics that has ideal properties, each having its advantages and disadvantages. An ideal material would have the following characteristics: not to be biologically dangerous for obvious reasons; be chemically and thermally stable, non-irritating and biocompatible; to meet aesthetic requirements - to have sufficient translucency and transparency; reasonably inexpensive in terms of minimum cost of materials and method of manufacturing, which should not be complex; to possess high mechanical properties; the patient should not feel the taste and smell of the material.

The metals used in dentistry, although they have almost ideal mechanical properties, good biocompatibility and a reasonable price, have a relatively high thermal and electrical conductivity, which is not indicated in the case of dental prostheses. Ceramic materials clearly dominate in terms of aesthetics, biocompatibility and bioinertity with adjacent tissues, but they are extremely expensive and have lower mechanical properties compared to metals.

Constructions made of polymeric materials have the advantage of easy manufacturing and low price, while the mechanical properties and longevity leave much to be desired. Following the analysis of all the important properties and characteristics of the materials used in the dental prosthetic field, I developed a calculation algorithm for choosing the optimal material, consisting in comparing the studied materials in terms of the main characteristics of dental prostheses. Based on this study, it is easier to review and choose the right material for each individual patient, depending on several parameters and factors [31]. Some sequences from the comparative study for biomaterials used in dental prosthetics are illustrated in fig. 4 and fig. 5.

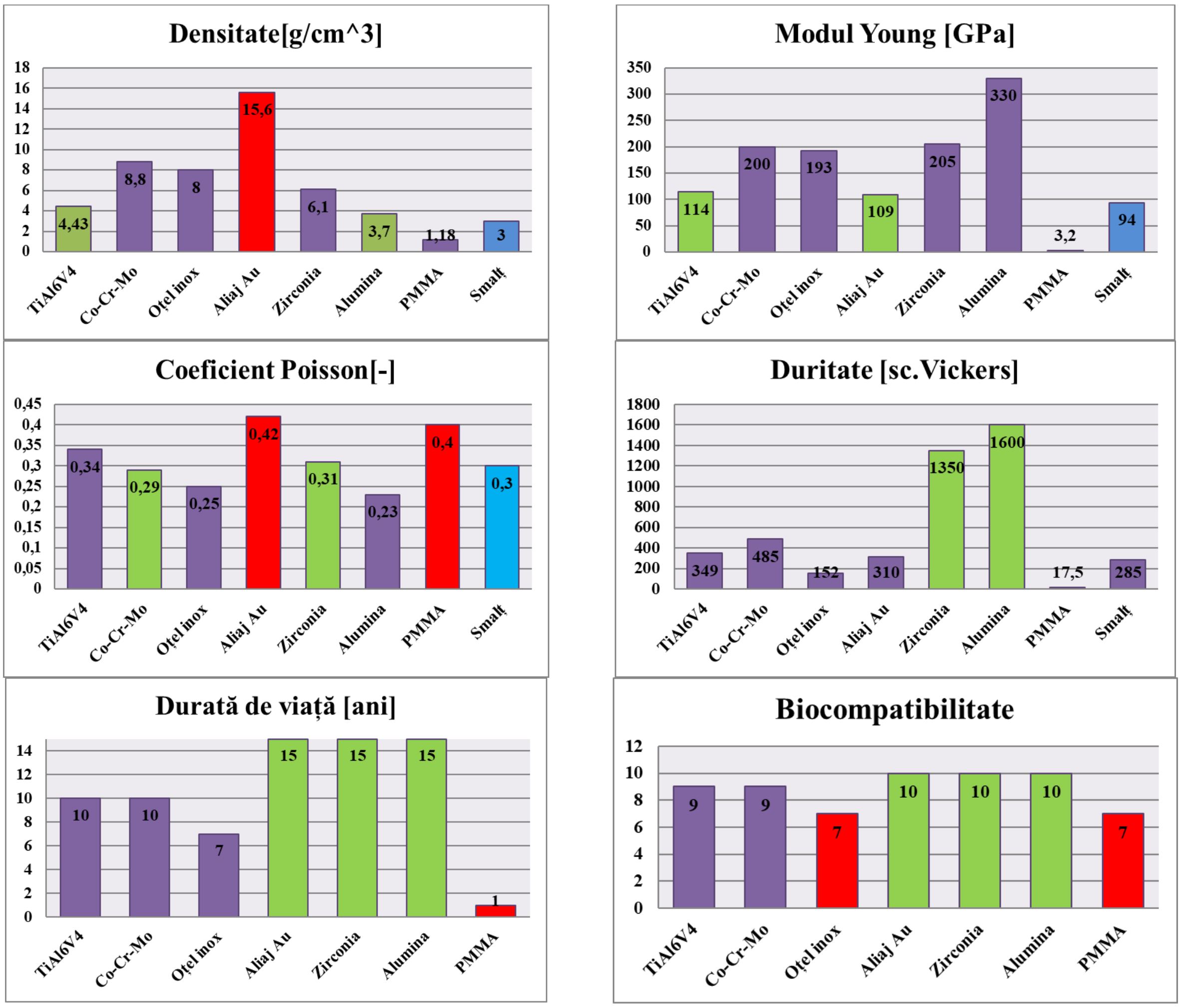


Fig. 4. Some results of the comparative study on the properties of biomaterials used in dental prosthetics

		Material						
Proprietate (Ci)	Pondere(Pi)	TiAl6V4	CoCrMo	Oțel inox	Au	Zirconia	Alumina	PMMA
Densitate	0.05	9	7	7	5	8	9	6
Modul Young	0.05	10	8	8	10	8	6	5
Poisson	0.05	8	10	8	6	10	7	6
Rez.compresiune	0.1	8	10	6	6	10	10	4
Rez.rupere	0.1	9	10	8	8	7	6	4
Duritate	0.05	8	8	6	8	10	10	4
Caldură specifică	0.05	8	8	8	6	8	10	6
Coef.dilatare term.	0.05	10	8	8	8	10	10	4
Conduct.termică	0.05	8	8	6	4	10	6	10
Biocompatibilitate	0.1	9	9	7	10	10	10	7
Rezistivitate electr.	0.05	8	8	8	6	10	10	10
Estetică	0.1	8	8	7	4	10	10	8
Cost	0.1	7	8	8	4	4	6	10
Durată viață	0.1	8	8	7	10	10	10	4
	1							
Total		8.35	8.55	7.25	6.85	8.8	8.6	6.25

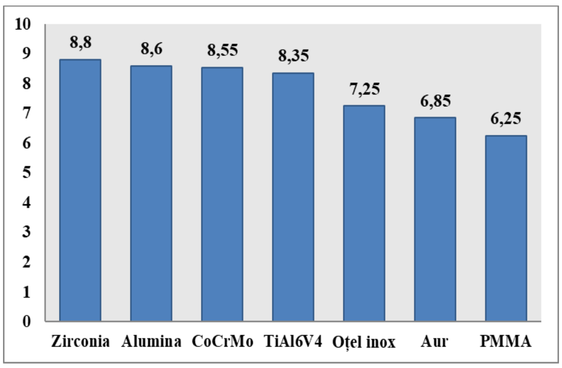


Fig. 5. The results of the analysis of the material characteristics

Chapter 4 "**Additive technologies for obtaining dental prostheses and their post-processing procedures**" presents the technologies and materials used in additive manufacturing with possible applications in the field of dental prosthetics and their post-processing procedures [31] [82] [89] [90] [93] [97] [98] [100] [102] [110] [115]. Fig. 6 presents some possible applications of experimentally researched additive technologies.

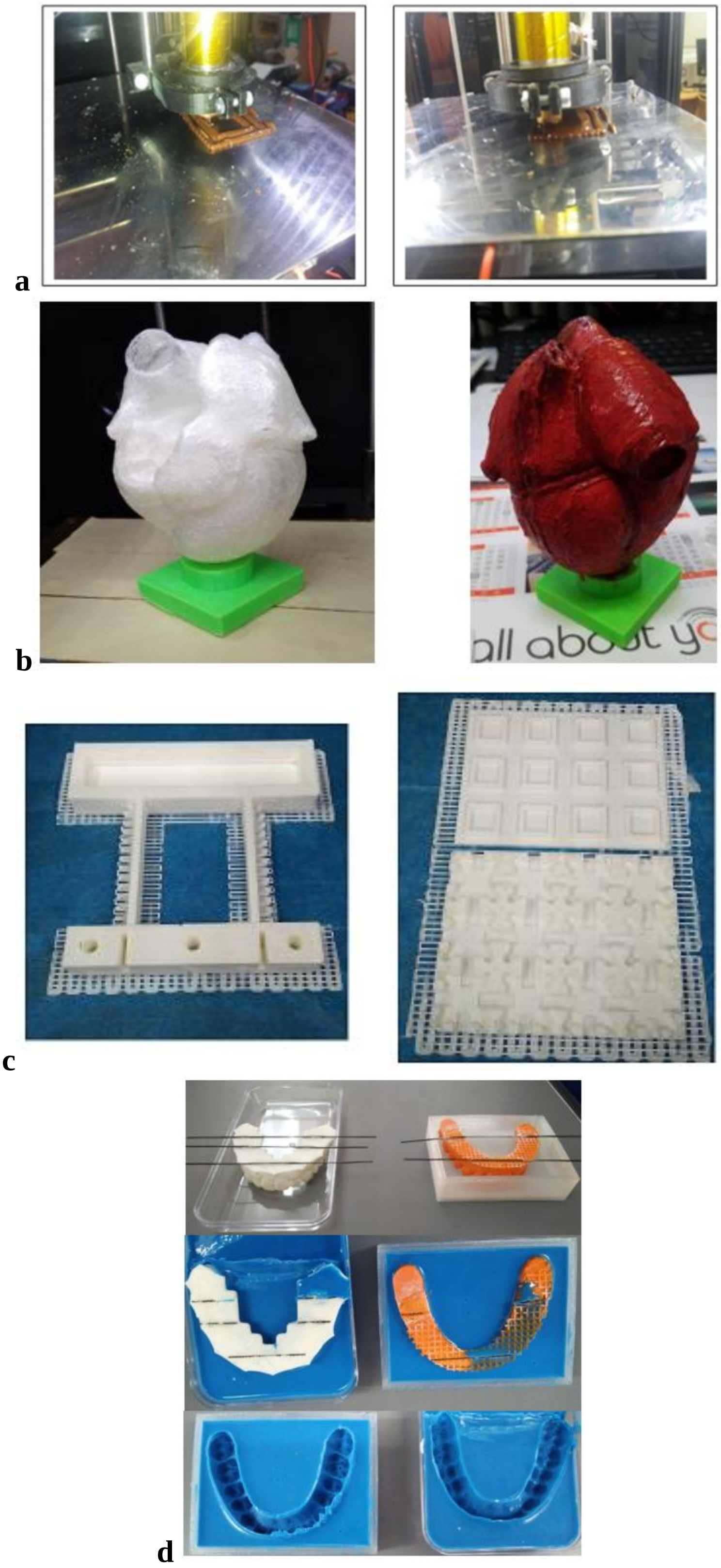


Fig. 6. Possible applications of the researched additive technologies: a - food field; b - anatomical prototypes; c - MEMS field; d - casting models

Also, in this chapter, the differences between the most important additive manufacturing methods were classified and highlighted according to several considerations. It have been identified the most popular 3D printing processes according to the principle of operation, according to the material used and the state of the raw material.

The main types of additive technologies with possible applications in dental prosthetics were presented (Fig. 7), as well as their post-processing procedures. They were classified according to the principle of operation and described, highlighting the advantages and disadvantages of each.

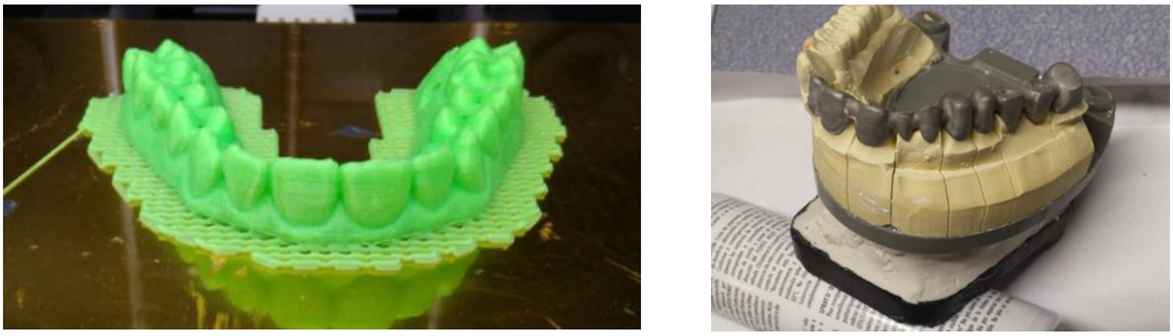


Fig. 7. Dental prosthetic model made by FDM thermoplastic extrusion and dental prosthesis made by selective laser melting

It can be concluded that additive manufacturing is becoming more and more important on the world market due to its exclusive properties, but the big problem remains the quality of printed surfaces, so post-processing steps are indispensable to obtain reliable dental prostheses with desired properties and high performance. Therefore, the finishing technologies were researched according to the additive process used. A classification was made of the post-processing processes of additive technologies, highlighting their major importance. Post-processing processes for metallic materials obtained by adding material are the most important, being a functional part, and not a prototype. In this case, being a dental bioprosthesis, the finish becomes crucial in order to obtain a prosthetic restoration that will not affect the patient and will have a long life. Fig. 8 shows dental prostheses realized of Co-Cr-W alloy made by selective laser melting in three different states of post-processing - raw, finished and mechanically polished, where it can be clearly observed how the operations of post-processing influences the appearance of prostheses. One of the most suitable methods of finishing these prostheses can prove to be the finishing by electrochemical polishing, as a result of which glossy-looking parts are obtained with improved fatigue resistance due to the elimination of residual stresses. It also increases the corrosion resistance following anodic polishing.

Fig. 8. Dental prostheses realized by selective laser depositiom in different states of post-processing

In **Chapter 5** entitled **"Results of experimental researches on the establishment of optimal parameters for realization of dental prostheses by selective laser melting and other additive technologies"** I presented the realization of dental prostheses and dental prosthetic models by three different additive technologies: powder bed fusion – selective laser melting/sintering, thermoplastic extrusion - FDM process and vat photopolymerization - DLP process. In addition, I presented the realization of dental prostheses by modern substractive techniques using specialized milling systems with high performance. I also presented the realization of additively manufactured customized individual dental models obtained on the basis of a digital intraoral scanning, as well as I performed simulations by finite element method of dental structures obtained by scanning [31] [97] [98] [122] [125] [130] [139] [141] [143].

Different equipment, raw materials, software systems and process parameters for printing were used to realize the dental prosthetic elements, and the obtained structures, materials and equipment were characterized and compared, being identified analysis and optimization solutions.

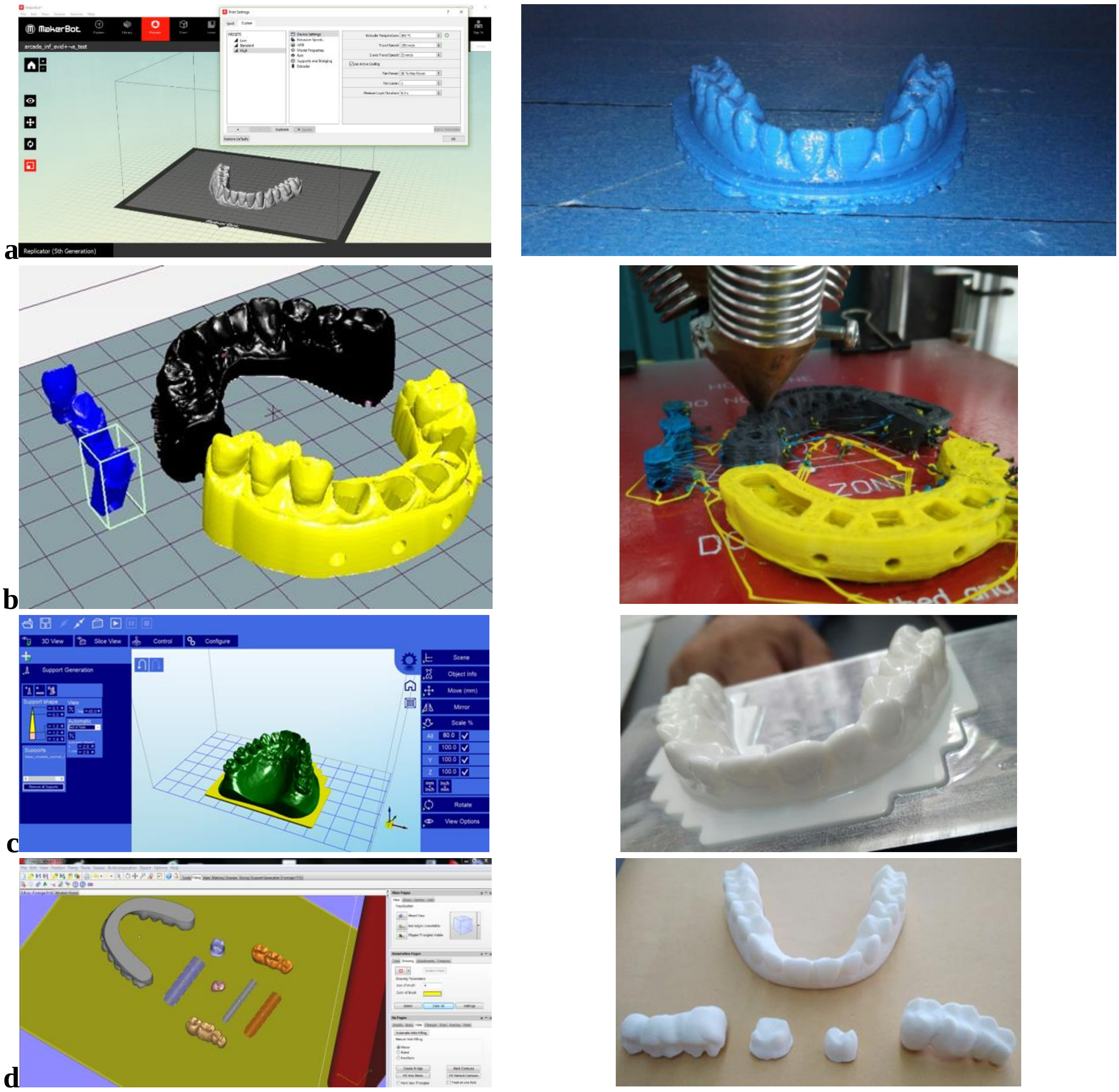


Fig. 9. Some software systems used and dental prosthetic models realized by various additive technologies: a - FDM on the Makerbot printer; b - FDM - multicolor printer with diamond type extruder; c – vat photopolymerization - Wanhao Duplicator 7 printer; d - selective laser sintering - SLS Formiga equipment

Fig. 10. The equipment used and the prostheses realized by selective laser melting in the raw and finished state

Fig. 10 shows the dental prostheses made by selective laser melting in raw and finished states, as well as the equipment used - Sisma MySint 100 installation.

The raw material in powder form and the dental prostheses made by selective laser melting from cobalt and chromium alloy were investigated microscopically, using powders with a different granulation (coarse> 50 µm and a mixture of fine powder <30 µm with powder coarse) and dental prostheses made by selective laser melting at different stages of post-processing (finished and polished) (Fig. 11).

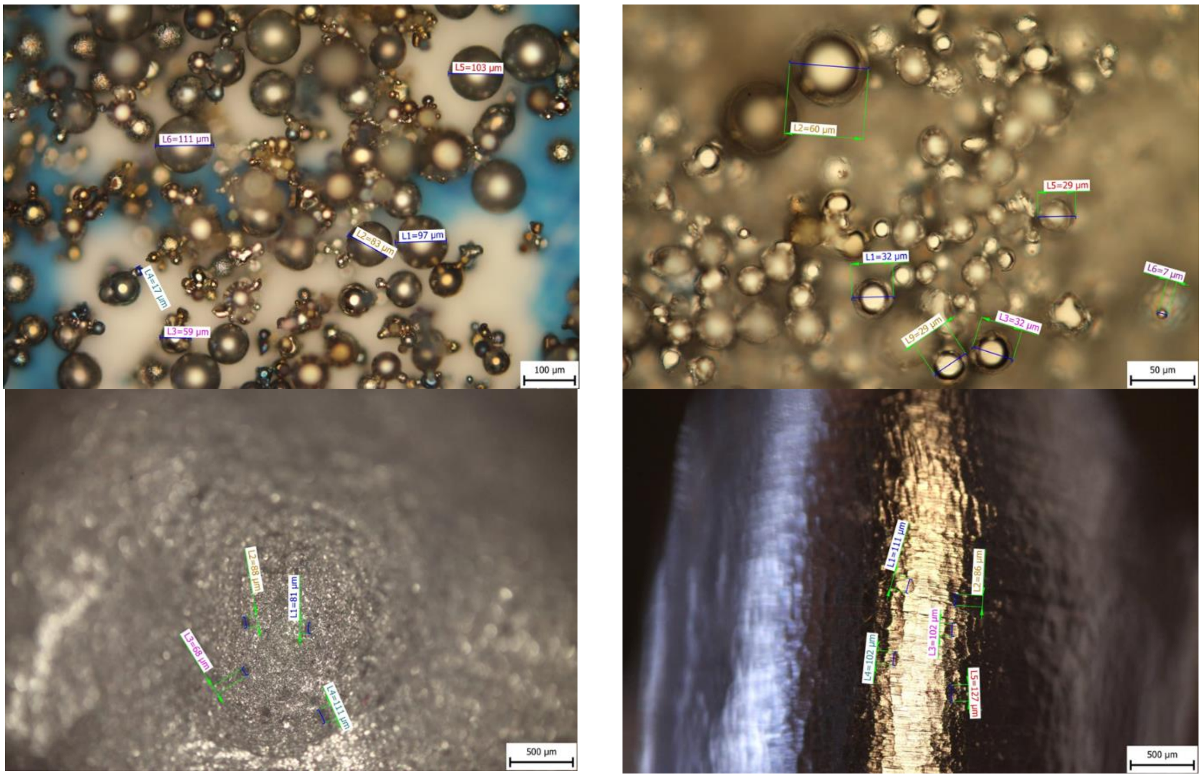


Fig. 11. Some results obtained regarding microscopic images of metal powder and finished and polished dental prostheses made by selective laser melting

I also obtained several dental customized models based on digital intraoral scanning (Fig. 12).

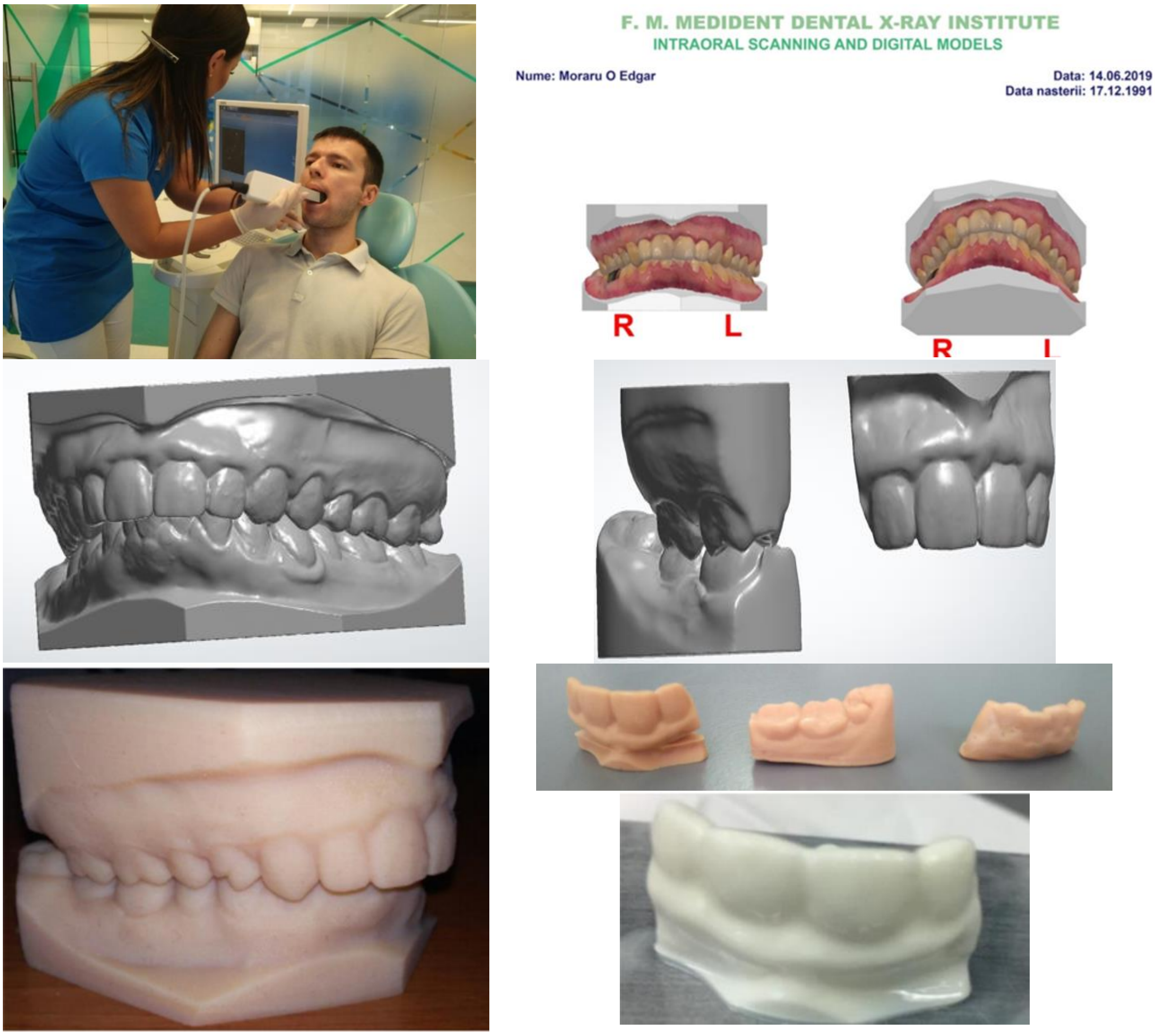


Fig. 12. Dental prosthetic structures obtained by additive technologies based on an intraoral digital scanning

The digital dental structures obtained by intraoral scanning were numerically simulated by the finite element method (Fig. 13). Several advanced software tools were used to simulate and process digital files obtained by intraoral scanning, including the possibility of using combined advanced tools for anatomical CAD design and engineering CAE analysis programs (Fig. 14) [151] [152].

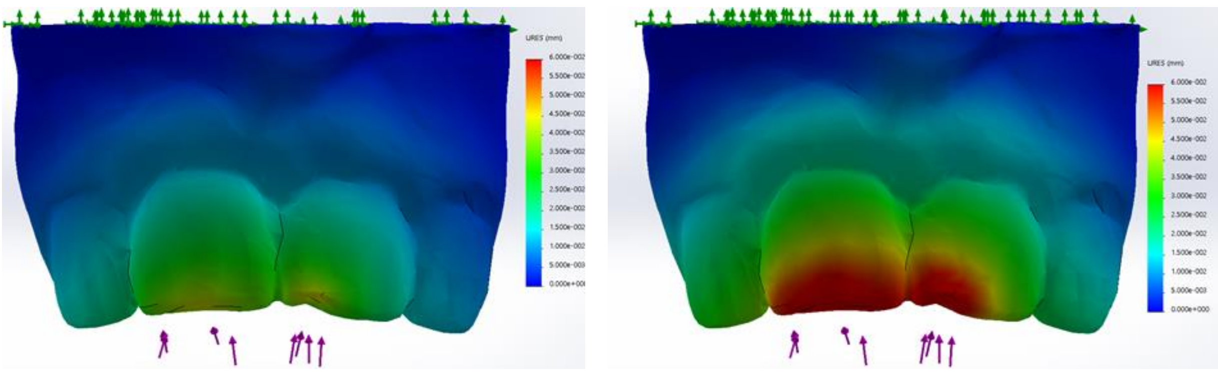


Fig. 13. Some results of the FEM analysis on the deformation of dental structures

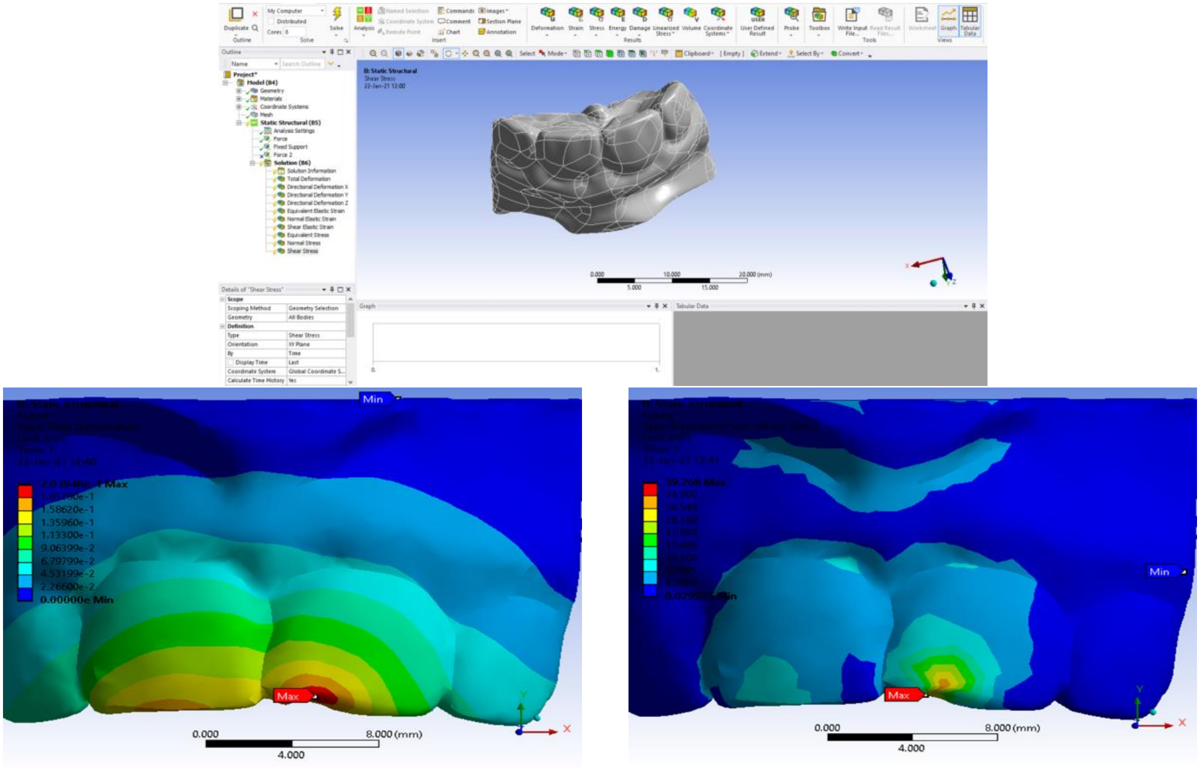


Fig. 14. Some results of the FEM analysis obtained in Ansys on the deformation of dental structures and the equivalent von Mises stress

In **Chapter 6 "Mathematical modeling of the selectiv laser melting process"** I presented the mathematical model developed for the thermal analysis of the selective laser melting process for realizing dental prostheses, to determine how the process parameters influence the final result of the prosthesis. It was presented a mathematical model regarding the thermal characteristics of the additive technology by selective laser melting, after which the temperature will be deduced as a function of time, the cooling rate, as well as the thermal acceleration during the melting process. I analyzed three different biomaterials used in dental prosthetics - titanium alloy, cobalt-chromium alloy and 316L stainless steel. I also analyzed the influence of some important parameters on the thermal characteristics in order to obtain dental prostheses with the best possible properties and characteristics [57] [153] [155] [158] [159] [162].

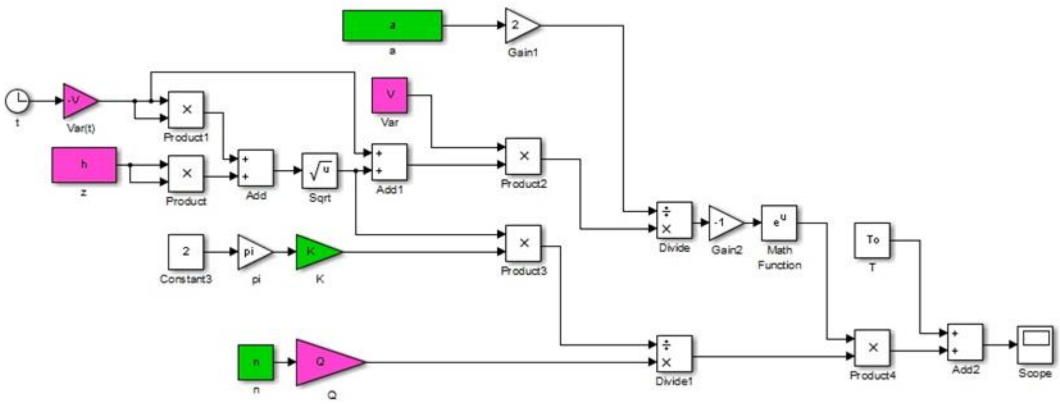


Fig. 15. Block diagram of the mathematical model for heat transfer during the selective laser melting process [158]

Some results obtained regarding the mathematical modeling of the selective laser melting process are presented in fig. 16, and some results regarding the study of the influence of some process parameters on the temperature of the biometals during the selective laser melting process are presented in fig. 17.

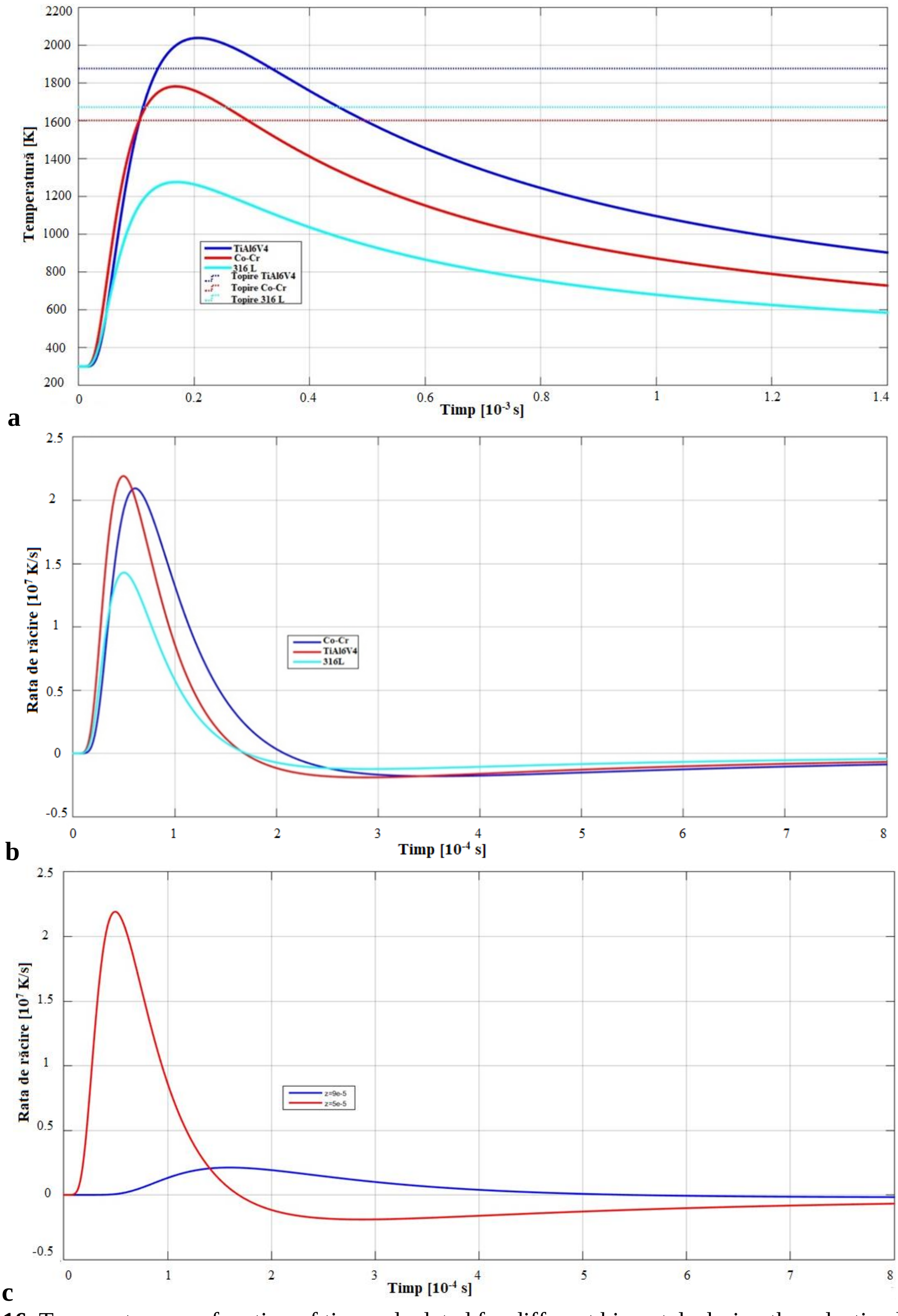


Fig. 16. Temperature as a function of time calculated for different biometals during the selective laser melting process (a), cooling rate calculated for different dental biometals (b) and cooling rate as a function of time calculated for Co-Cr at z = 40 μm and z = 90 μm (layer thickness)

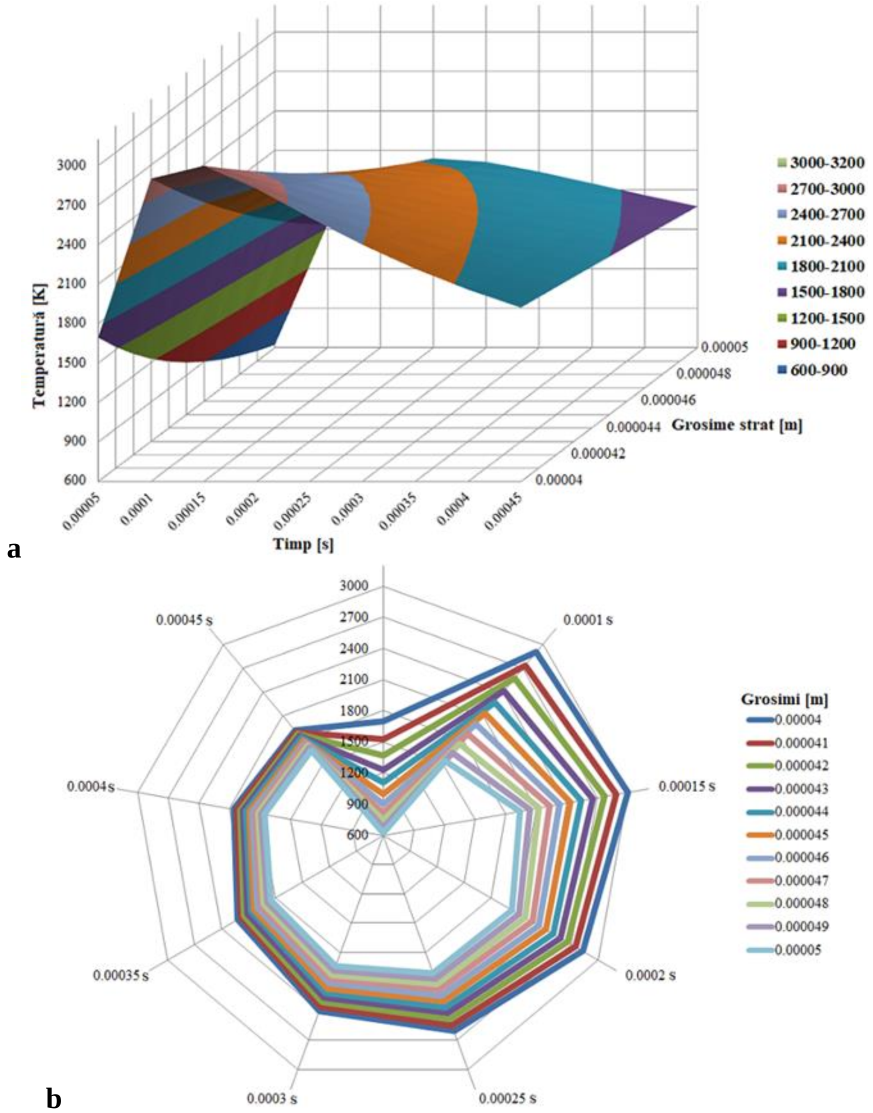


Fig. 17. Some results regarding the study of the influence of some process parameters on the temperature of biometals during the selective laser melting process: a - temperature calculated as a function of time and layer thickness for TiAl6V4; b - temperature distribution over time for different thicknesses of the powder layer for TiAl6V4

This mathematical modeling demonstrates that titanium alloy and cobalt-chromium alloy have better thermal properties and are easier to process by selective laser melting, compared to stainless steel, which needs higher energy consumption to could be processed in optimal conditions. The study in this chapter could be a theoretical solution for determining the thermal characteristics during the process of selective laser melting. Based on the modeling of heat transfer, as well as on the study of the influence of some process parameters on the temperature during selective laser melting, it can be concluded that, because the studied metals have very different thermal and physical properties, their behavior during selective melting laser is significantly different, the study of the properties of materials being very important to obtain dental prostheses with the best possible characteristics [158].

Chapter 7 entitled "**Results of experimental researches on the characteristics and properties of dental prostheses realized by selective laser melting and other additive technologies**" presents the characterization of dental prostheses obtained by selective laser melting and dental prosthetic models made by thermoplastic extrusion and vat photopolymerization using modern analysis equipment and systems. I studied the mechanical behavior of dental structures at various loads, accuracy, surface condition, chemical composition, wear resistance and some mechanical properties, comparing materials, technologies and equipment with which dental prosthetic elements were realized.

In subchapter 7.1 it was presented the behavior of dental prosthetic models from different materials and realized by different additive technologies, which were subjected to mechanical loads [165] [166] [167]. To study the mechanical behavior at various compression forces, a force transducer from the Imada experimental stand was used, using several types of accessories and testing several materials and technologies that can be used to execute dental prosthetic models (Fig. 18).

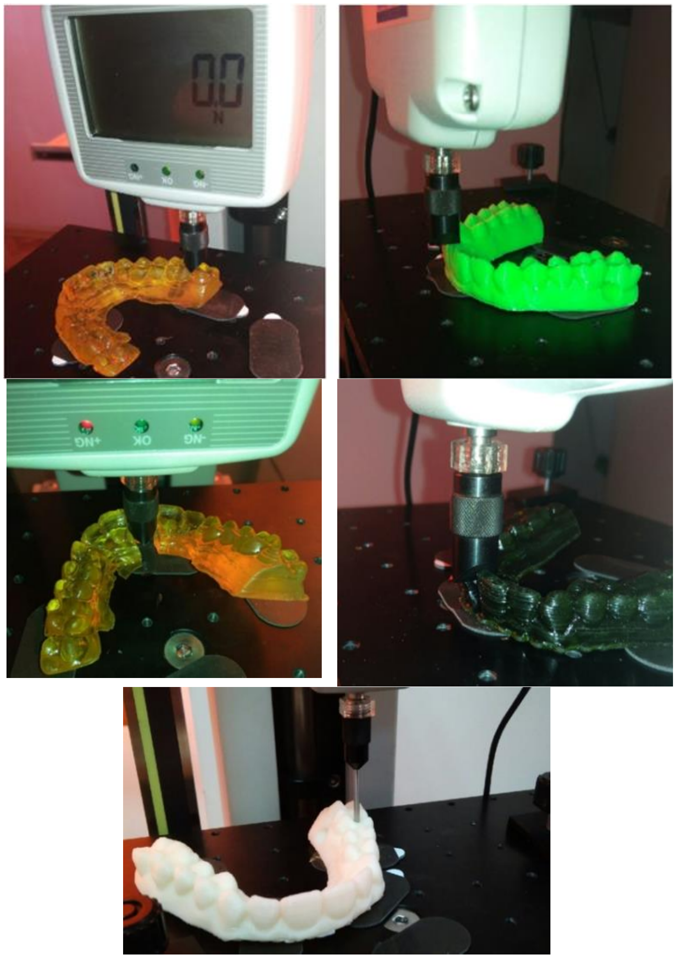


Fig. 18. Dental prosthetic models on the test stand

These dental prosthetic models made by additive technologies can be used to correctly diagnose and choose the appropriate therapy, improving communication between different teams of specialists or the dialogue between the dentist and the patient. Also, the three-dimensional physical model can be used in planning surgeries with a high degree of complexity, which can be practiced on these models or to use them for teaching purposes for future specialists in the field.

Several dental prosthetic models made by various different additive technologies have been subjected to mechanical stresses of compression in two different areas. The maximum deformations were determined, as well as the force at which they were obtained. As expected, thermoplastic prototypes are more mechanically resistant, ABS proving its usefulness in many engineering applications. The biocompatible material, which in optimal printing conditions could even serve as temporary prostheses, proved to be just as resistant. Maximum deformations are obtained in PETG dental prosthetic models. In the prosthetic models from photopolymer resin, the breakage in the central incisor area was obtained at approximately 350 N. Some results obtained regarding the mechanical behavior of the dental models made by additive technologies are presented in fig. 19.

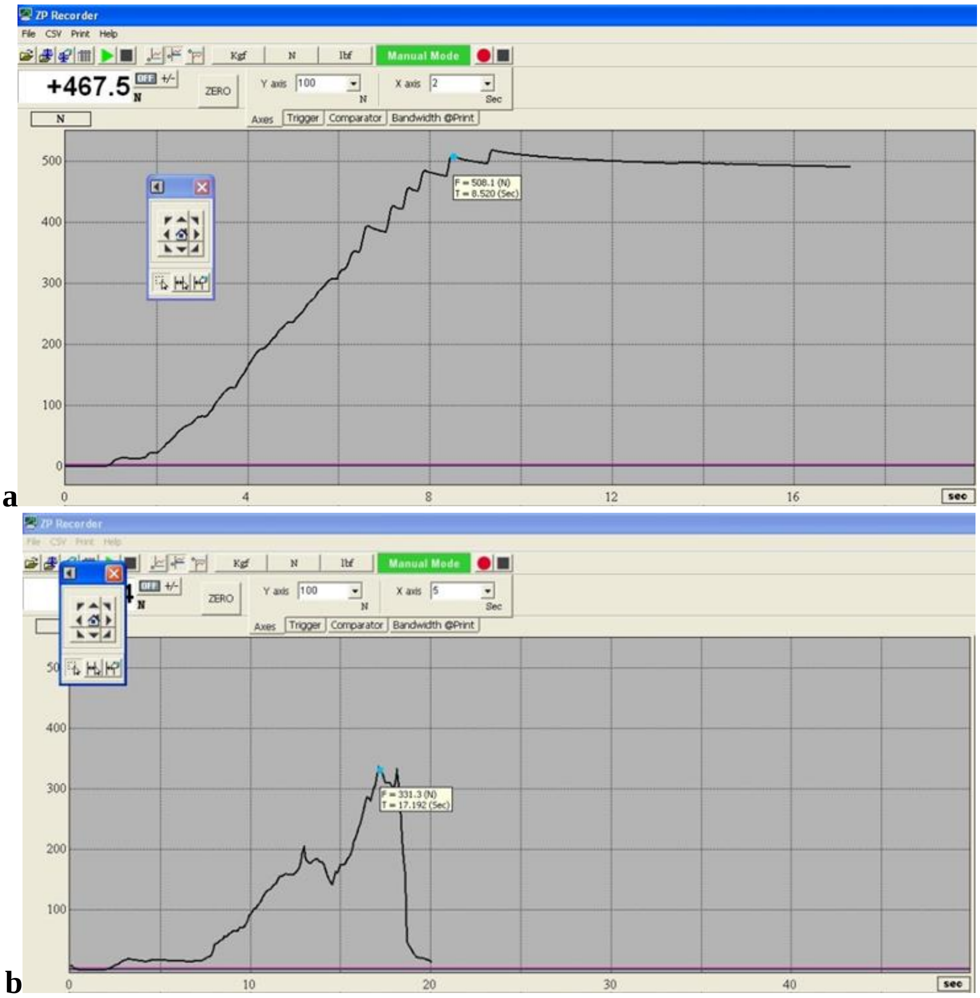


Fig. 19. Some results obtained regarding the mechanical behavior of dental models made by additive technologies: the evolution of the force as a function of time of the thermoplastic dental prototype from ABS for loads in molar area - Fmax = 500 N (a) and the evolution of the force as a function of time of the dental prototype from standard photopolymer resin for loads in central incisor area (b)

Also, the experimental study on the mechanical behavior of dental models obtained by different additive manufacturing methods and using different materials and equipment reveals linear evolutions of the deformation-force characteristics for both the incisor area and the molar area for almost all tested materials, except for a region in the initial field of deformations (close to the origin of the coordinate system). In the case of the molar region, higher deformation forces were obtained than in the case of the incisor region, given their structure. In terms of materials used, nylon and PLA showed the best linear behavior. In general, all additive technologies that have been used to realize dental prosthetic models have led to characteristics close to the linear ones after testing them. In the case of FDM technology, an almost linear behavior was obtained only for the dental prosthetic models from PLA made on Makerbot and Wanhao 3D printers. PLA is a relatively biodegradable material and has shown a stable mechanical behavior, so it can be used as a model in dentistry if FDM technology is considered. The same can be said about SLS and DLP technologies, which help to obtain much more accurate and high-quality models, but at the same time are more expensive than those made by FDM technology [166] [167]. Some results regarding the mechanical analysis of the dental prosthetic models executed by different technologies and using different 3D printing equipment are presented in table 1 and fig. 20.

Table 1. Experimental results of force-deformation characteristic in the incisor and molar region for dental models made by three different additive technologies [167]

Nylon (SLS)				Photopolym. resin (DLP)				PLA (FDM, Makerbot)			
Incisor region		Molar region		Incisor region		Molar region		Incisor region		Molar region	
δ (mm)	F (N)	δ (mm)	F (N)	δ (mm)	F (N)	δ (mm)	F (N)	δ (mm)	F (N)	δ (mm)	F (N)
0	0	0	0	0	0	0	0	0	0	0	0
0,1	1,6	0,2	3,4	0,1	11	0,2	22	0,1	3	0,2	5,5
0,2	2,8	0,4	13	0,2	21	0,4	53	0,2	9,5	0,4	8
0,3	5,7	0,6	30	0,3	28	0,6	95	0,3	21	0,6	25
0,4	7,5	0,8	40	0,4	31	0,8	152	0,4	36	0,8	56
0,5	11,5	1	56	0,5	44	1	220	0,5	56	1	117
0,6	20	1,2	86	0,6	55	1,2	283	0,6	71	1,2	185
0,7	28,2	1,4	129	0,7	64	1,4	353	0,7	83	1,4	245
0,8	38	1,6	205	0,8	70	1,6	430	0,8	103	1,6	312
0,9	47	1,8	295	0,9	75			0,9	114	1,8	408
1	57	2	386	1	92			1	145		
1,1	68			1,1	98			1,1	153		
1,2	75			1,2	111			1,2	166		
1,3	90			1,3	126			1,3	180		
1,4	106			1,4	130						
1,5	118			1,5	151						
1,6	130			1,6	170						
1,7	146			1,7	182						

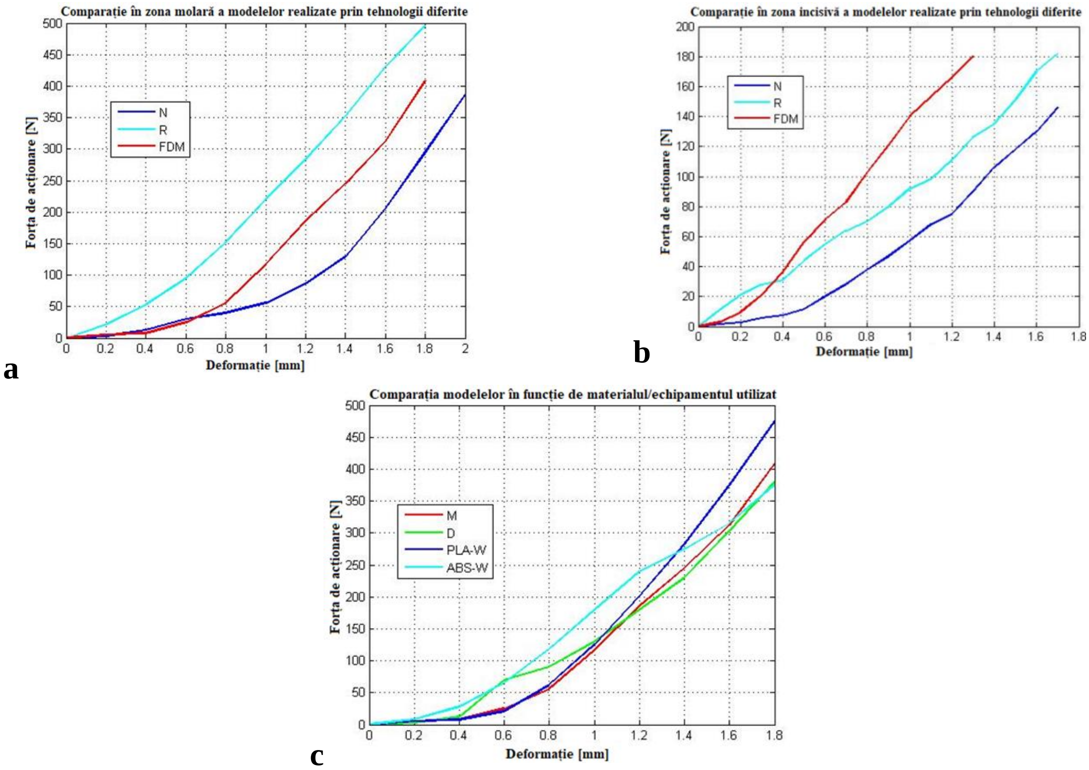


Fig. 20. Some results obtained regarding the comparative mechanical analysis of dental prosthetic models realized by additive technologies: comparative results according to the technology used in the molar area (a), comparative results according to the technology used in the incisor area (b), comparative results of FDM models in function of the material and 3D printer used (c).

In order to validate the results of experimental research on testing at some mechanical loads of dental prosthetic models realized by additive technologies, they were compared with the data obtained from the simulation by FEM analysis. For this purpose, the dental model of the incisor teeth obtained by digital intraoral scanning was used, which was simulated in the subchapter 5.8, and subsequently several models (PLA) were printed which were subjected to compression forces using an accessory with a tip shape approximately similar to the force actuation area in the Ansys simulation. Relatively close results were obtained between the deformations of the dental models obtained experimentally and theoretically numerically, which validates the research methods used (Fig. 21).

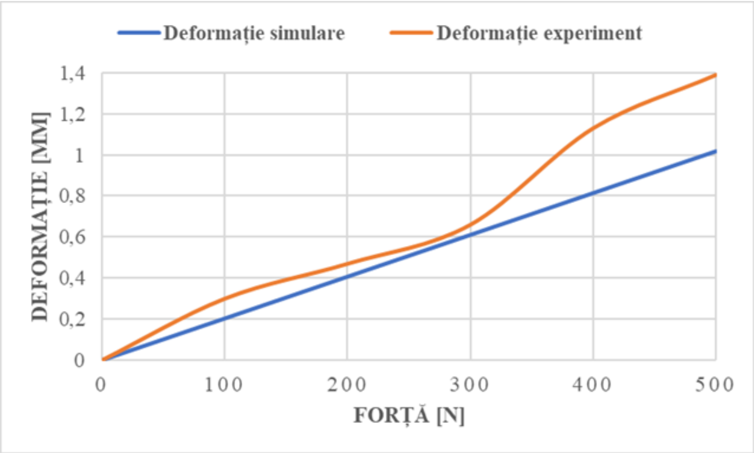


Fig. 21. Comparison of experimental results with those of the simulation regarding the deformation of dental prosthetic models

The aim of the researches in subchapter 7.2 was to estimate the most suitable materials in terms of wear resistance for the realization of dental prosthetic models by FDM thermoplastic extrusion technology [171]. In order to be able to estimate the wear of the thermoplastic materials used to realize dental prosthetic models, eight gears with the same module and number of teeth were made using FDM technology from the following materials: 3 from PLA, 3 from ABS and one from PETG reinforced with carbon fiber and nylon. In order to determine the wear of the gears that require a continuous and constant operation, a demonstration stand was designed and constructed to highlight the degree of wear following the continuous operation of the eight gears made by additive technologies.

a

b

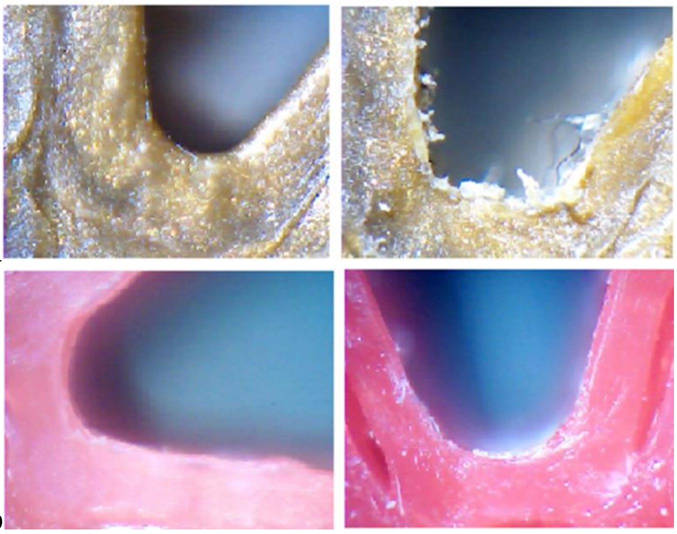


Fig. 22. Some results obtained regarding wear resistance research: comparison of thermoplastics before and after testing - ABS (a) and PLA (b)

PLA has proven to be the best in terms of wear resistance and from this perspective can be considered the most suitable material for the realization of dental prosthetic models through additive manufacturing technologies. Despite better mechanical properties of printed ABS structures, they are more worn after a continuous use cycle than PLA elements. The conclusions drawn after this experimental research [171] on the wear of thermoplastic materials obtained by additive technologies can be useful in choosing the optimal solution for the realization of dental models with specific applications in dentistry.

Regarding the dimensional accuracy of dental prosthetic models realized by additive technologies (subchapter 7.3.1), in order to compare the materials, additive technologies and equipment used to realize dental models in terms of dimensional accuracy, as well as their reproducibility or repeatability, it was designed and realized relatively simple pieces with the same dimensional characteristics, shown in fig. 23, which unlike dental prosthetic models can be studied and tested according to known standard procedures.

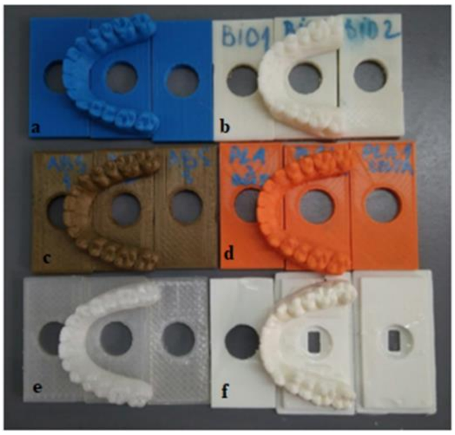


Fig. 23. Test pieces realized: a - PLA (MakerBot), b - biocompatible ABS (Wanhao), c - ABS (Wanhao), d - PLA (Delta), e - PLA (Wanhao), f - photopolymer resin

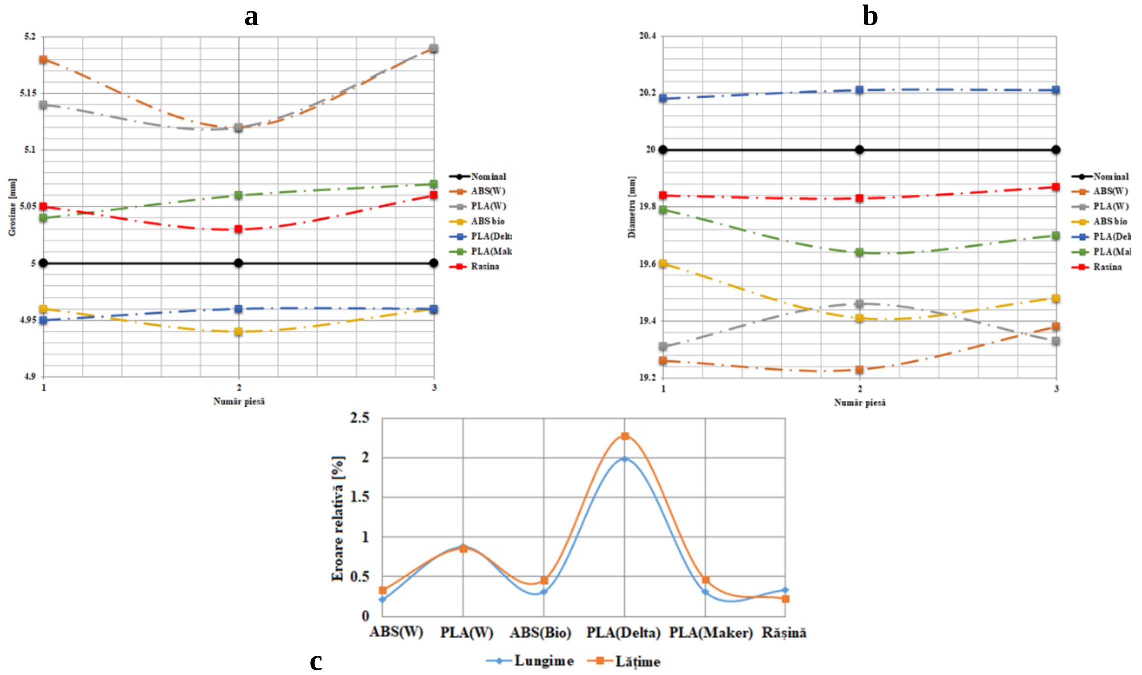


Fig. 24. Some results obtained on the dimensional accuracy of dental prosthetic models: measured dimensions of thickness and diameter (a and b) compared to the nominal size, comparison of average relative errors for length and width (c)

Tabel 2. Measured values for test pieces

Material	Nr	Length Nominal 70 mm		Width Nominal 35 mm		Thickness Nominal 5 mm		Diameter Nominal 20 mm	
		Value [mm]	*Error [%]*	*Value [mm]*	*Error [%]*	*Value [mm]*	*Error [%]*	*Value [mm]*	*Error [%]*
ABS Wanhao	1	69.87	0.19	35.08	0.22	5.18	3.47	19.26	3.84
	2	69.85	0.21	35.12	0.34	5.12	2.34	19.23	4
	3	69.84	0.23	35.15	0.43	5.19	3.66	19.38	3.20
Average error		**0.21**		**0.33**		**3.16**		**3.68**	
ABS Medical	1	69.8	0.29	34.79	0.6	4.96	0.8	19.6	2.04
	2	69.73	0.39	34.84	0.46	4.94	1.21	19.41	3.04
	3	69.82	0.26	34.89	0.32	4.96	0.8	19.48	2.67
Average error		**0.31**		**0.46**		**0.94**		**2.58**	
PLA Wanhao	1	69.32	0.98	34.74	0.75	5.14	2.72	19.31	3.57
	2	69.46	0.78	34.78	0.63	5.12	2.34	19.46	2.77
	3	69.39	0.88	34.59	1.19	5.19	3.66	19.33	3.47
Average error		**0.88**		**0.86**		**2.9**		**3.27**	
PLA Delta	1	71.45	2.03	35.86	2.4	4.95	1.01	20.18	0.89
	2	71.43	2	35.77	2.15	4.96	0.8	20.21	1.04
	3	71.38	1.93	35.82	2.29	4.96	0.8	20.21	1.04
Average error		**1.99**		**2.28**		**0.87**		**0.99**	
PLA Maker	1	70.22	0.31	35.08	0.22	5.04	0.79	19.79	1.06
	2	70.18	0.26	35.2	0.56	5.06	1.18	19.64	1.83
	3	70.26	0.37	35.22	0.62	5.07	1.38	19.7	1.52
Average error		**0.31**		**0.47**		**1.12**		**1.47**	
Resin	1	70.25	0.35	35.07	0.2	5.05	0.99	19.84	0.81
	2	70.28	0.4	35.09	0.26	5.03	0.6	19.83	0.86
	3	70.17	0.24	35.07	0.2	5.06	1.18	19.87	0.65
Average error		**0.33**		**0.22**		**0.92**		**0.77**	

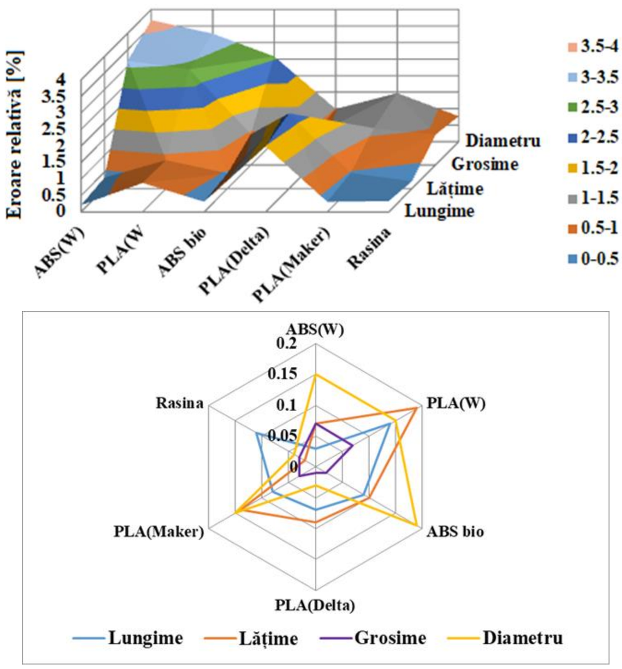


Fig. 25. Some results on the dimensional accuracy of dental prosthetic models: comparison of average relative errors (a) and radar reproducibility diagram (b)

This study may be useful for selecting the optimal material for dental models with specific applications that require high accuracy. As a material, the photopolymer resin gives the best results in terms of dimensional accuracy, which was to be expected. As equipment, the MakerBot 3D printer can be highlighted with constant and acceptable average relative errors, and Delta and Wanhao Duplicator 4S presenting problems at certain dimensions in relation to dimensional accuracy. These problems can be solved by calibrating the printers or checking the extrusion nozzle for minor clogging or setting a lower value for the thickness of the deposited layer in the software.

In general, acceptable average relative errors were obtained in most cases with values close to other studies from the literature [173].

Subchapter 7.3.2 presents the establishment of temperature ranges for additive technologies used to realize dental prosthetic models [175]. In subch. 7.3.1 I have highlighted the existing dimensional deviations from the nominal ones for the parts made by thermoplastic extrusion, and a possible cause for the appearance of these deviations is the contraction of the material in the cooling process, therefore, it is necessary to investigate how the material cools after it has been made by this technology. For the purposes described above I used a FLIR thermal camera (Fig. 26).

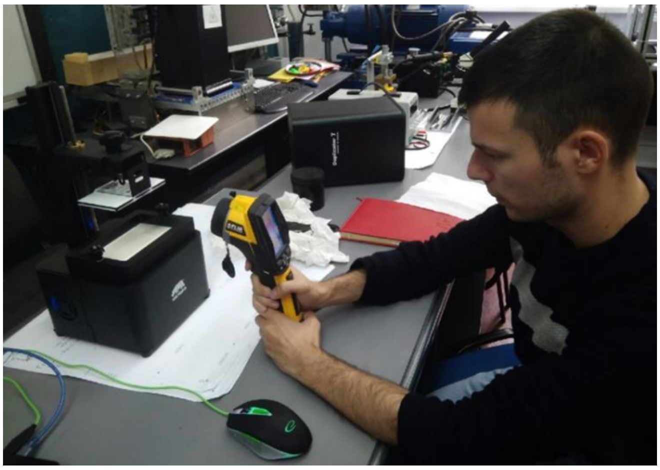


Fig. 26. Determining the temperature with the help of the FLIR thermal camera

Some results of the thermographic analysis of dental prosthetic models are presented in fig. 27.

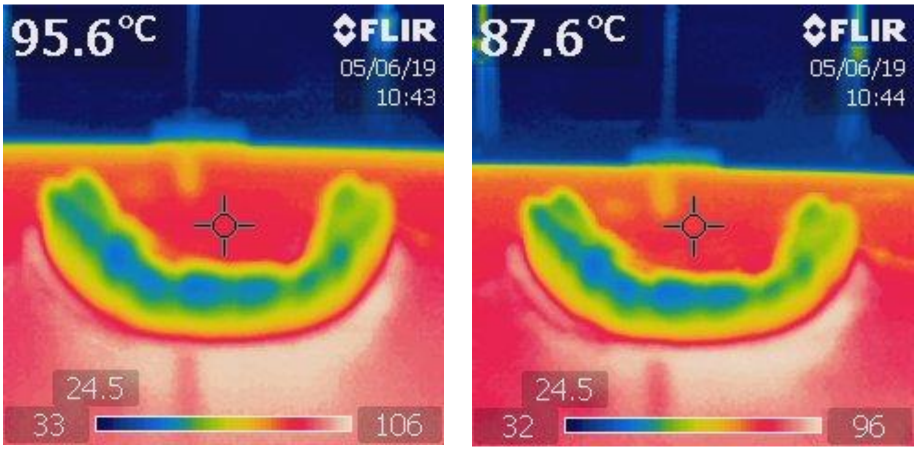


Fig. 27. Thermal images of dental models after completing the printing process

Among the research in this subchapter was the study of how the printed structure cools: after printing, I took captures for the dental model every 5 seconds for a minute, to see how the material cools over time. From the “Analyze” menu of the program I set three points of interest: the work platform, the central incisor area and the molar area, and the results obtained are shown in fig. 28.

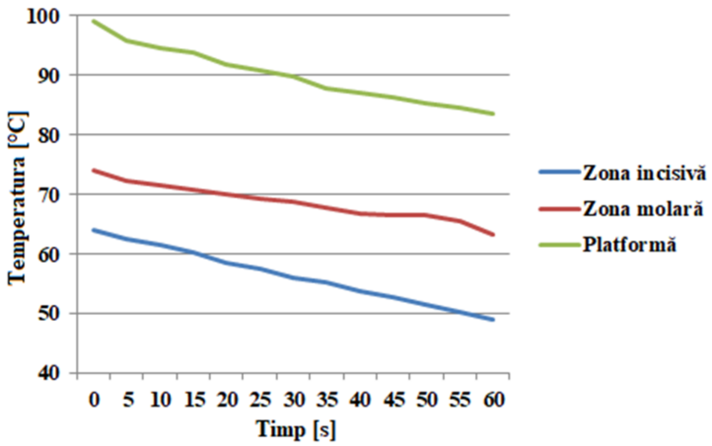


Fig. 28. Temperature as a function of time after printing in the 3 areas of interest

Considering the results obtained in subch. 7.3.1 on the dimensional accuracy of elements made by additive technologies, in subchapter 7.3.3 I realized an experimental study on the thickness of the deposited layers of models obtained by thermoplastic extrusion to demonstrate the possible cause of dimensional errors (on the z axis - thickness) and see the actual deviations from the nominal thickness imposed in the equipment software before production. For this purpose I investigated the test parts treated in subch. 7.3.1, as follows: ABS, PLA and biocompatible ABS printed on Wanhao printer (nominal layer thickness - 0.27 mm), PLA on Delta and Makerbot printers (in both cases the nominal layer thickness - 0.2 mm). The equipment used was Nikon iNEXIV VMA-2520 (Fig. 29).

Fig. 29. Nikon iNEXIV VM-2520 measuring system used to determine the thickness of the deposited layers

For all the investigated pieces, ten thicknesses of the layers deposited consecutively for each were measured and estimated, and fig. 30 presents some results for these determinations, observing from the equipment software the microscopic image of the studied parts on the left and the calculation of the thicknesses for the ten layers on the right.

After determining the thickness of the layers for the five parts and in order to compare the results obtained, I calculated some important parameters that will describe and estimate the way the layers were deposited, and in table 3 and fig. 31 I presented all the results obtained and the parameters determined based on these results.

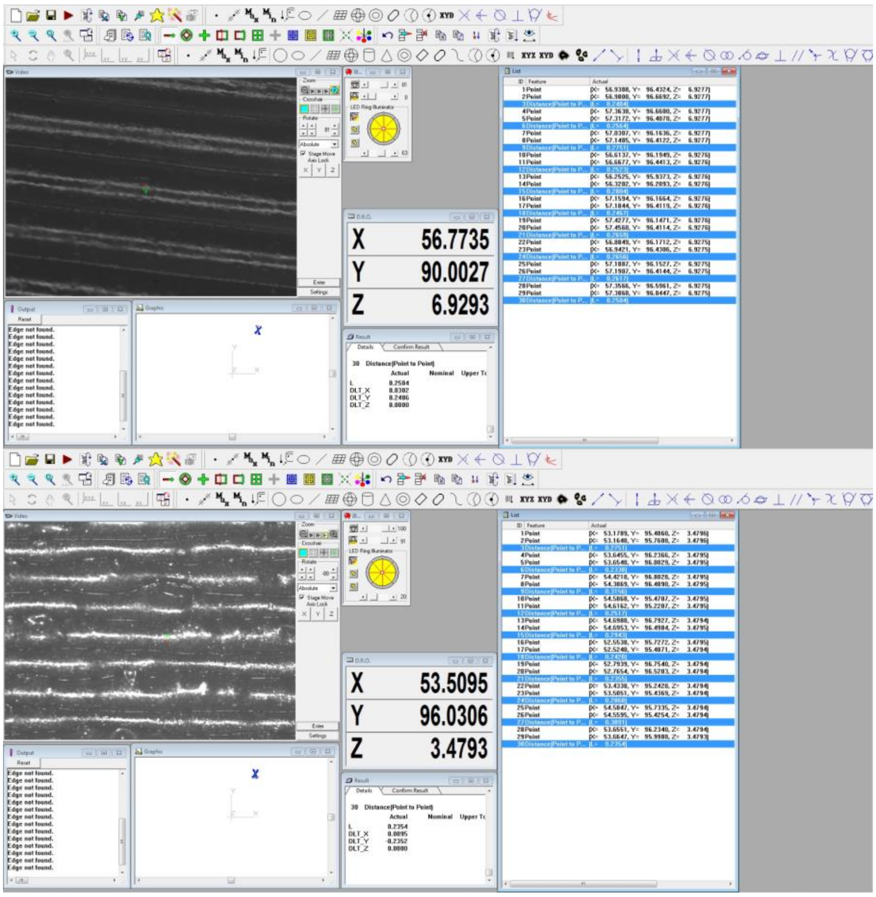


Fig. 30. Some results obtained regarding the determination of the thickness of the deposited layers

Tabel 3. Results of the determinations of the thickness of the deposited layers

Layer	Material (3D printer), nominal layer thickness				
	ABS bio (Wanhao) 0,27 mm	**ABS (Wanhao) 0,27 mm**	**PLA (Wanhao) 0,27 mm**	**PLA (Delta) 0,2 mm**	**PLA (Makerbot) 0,2 mm**
1	0,2502	0,2751	0,2404	0,2110	0,2062
2	0,2658	0,2338	0,2564	0,1929	0,2051
3	0,2666	0,3156	0,2751	0,1920	0,1964
4	0,2718	0,2943	0,2523	0,2100	0,1951
5	0,2676	0,2420	0,2804	0,2142	0,2003
6	0,2691	0,2355	0,2467	0,2212	0,2037
7	0,2622	0,2068	0,2659	0,1836	0,1919
8	0,2663	0,3091	0,2656	0,1818	0,1971
9	0,2700	0,2354	0,2617	0,2053	0,1924
10	0,2646	0,2355	0,2504	0,2230	0,2126
x_{med}	**0,2654**	**0,2583**	**0,2595**	**0,2035**	**0,2001**
ε_{rm} [%]	**1,7**	**4,32**	**3,89**	**1,75**	**0,05**
A_{max}	**-0,0198**	**-0,0632**	**-0,0296**	**0,023**	**0,0126**
D	**0,0216**	**0,1088**	**0,04**	**0,0412**	**0,0207**
σ^2	**0,0000361**	**0,00139**	**0,000159**	**0,000224**	**0,000045**
σ	**0,006**	**0,0373**	**0,0126**	**0,0149**	**0,00671**

Following this study it is possible to estimate and compare the variation of the thickness values of the deposited layers with respect to the nominal size and the variance with respect to their central tendency, being able to appreciate the most homogeneous material to obtain values of layer thickness as close as possible of their average in order to choose the best material from this point of view and to obtain the final model with appropriate dimensional characteristics. In order to have more conclusive results and to avoid possible random errors, determinations can be made for larger samples, this study having as main purpose the comparison of materials and equipment used to realize parts by thermoplastic extrusion.

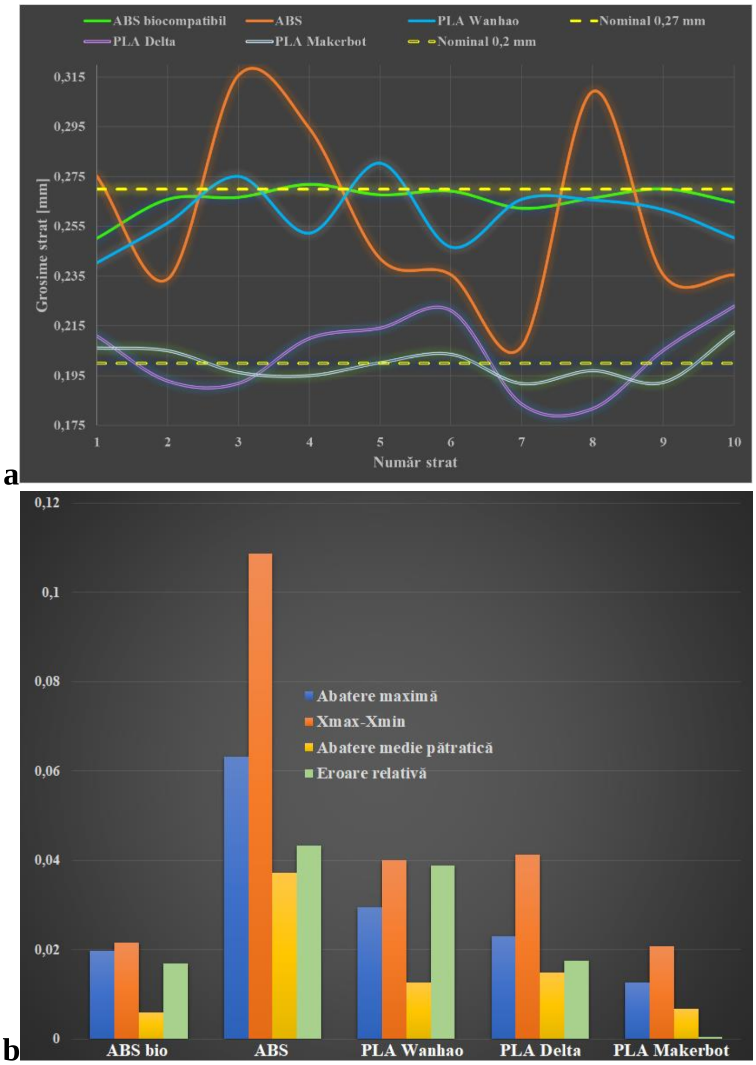
a
b


Fig. 31. Comparison of the determined layer thicknesses (a) and comparison of the parameters established following the determination of the layer thickness (b)

Considering the way in which the roughness of the surfaces of the dental prostheses influences their performance in time, I determined in subchapter 7.3.4 the microtopography of the surfaces of the dental prostheses made by selective laser melting, prostheses being in raw state, finished and mechanically polished (with abrasive particles) [181], the material being the cobalt-chromium-tungsten alloy, and their topographic characterization was performed using an NTEGRA Probe NanoLaboratory NT – MDT atomic force microscope [182] (Fig. 32).

Determinations of nanoroughness and characterization of surface microtopography was performed using the AFM microscope by scanning areas of 35x35 μm located in different places on the surface of the three investigated dental prostheses in various stages of post-processing (a total of 10 different areas were investigated for the three dental prostheses), and the parameters of interest were determined using the software of the equipment used NOVA SPM.

For the three investigated prostheses in different post-processing stages, the main roughness parameters were taken into account: the arithmetic mean deviation of the surfaces, the mean square deviation and the distance between the extremities of the irregularities (highest peak and deepest gap, respectively). Given that the measurements will not only address the surface profile, but two-dimensional cases - will be noted with S_a - the arithmetic mean deviation, S_q the quadratic mean deviation and S_y the distance between the extremities of irregularities / asperities, being area parameters in this case equivalent to those of profile. Some microtopographic images for prostheses in different stages of post-processing are shown in fig. 33.

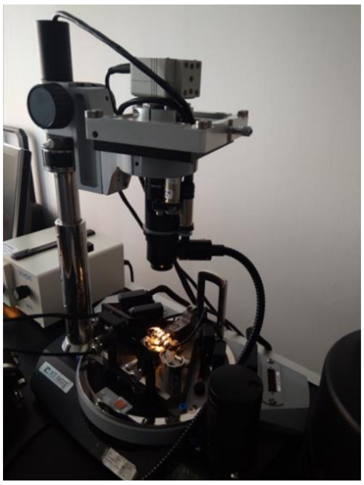


Fig. 32. Determination of nanoroughness of dental prostheses on an AFM microscope

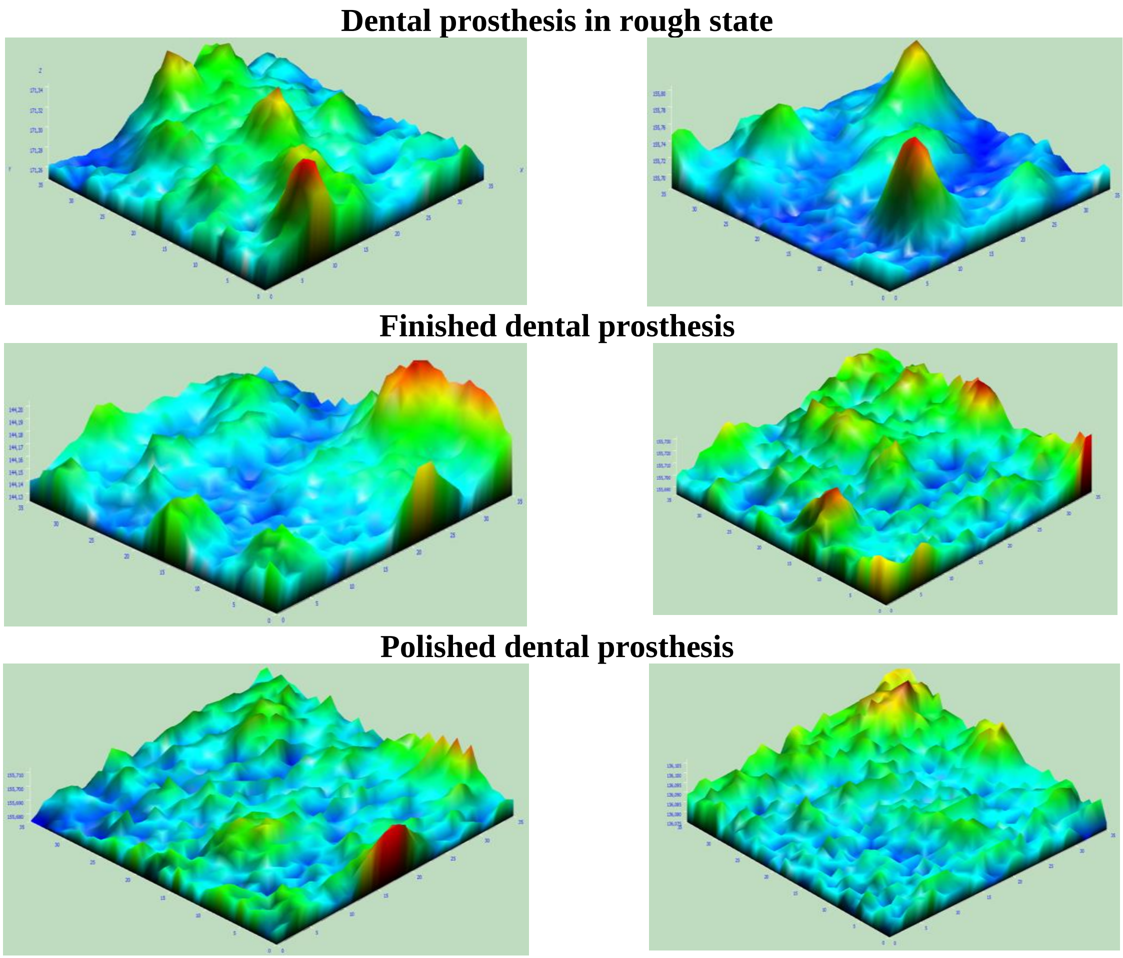


Fig. 33. Some microtopographic images obtained for the surfaces of dental prostheses (35x35 μm)

In table 4, I presented the parameters determined for the arithmetic mean deviation, the distance between the extremities of the irregularities and the quadratic mean deviation of the surfaces of 35x35 μm of the dental prostheses in different stages of post-processing, and fig. 34 presents a comparative graphical study for the average values of the arithmetic and quadratic mean deviations obtained following the determination of the surface microtopography for the three types of prostheses.

Tabel 4. Roughness parameters determined for dental prostheses in different stages of processing

Nr. Crt.	***Rough state prosthesis*** 			***Finished prosthesis*** 			***Polished prosthesis*** 		
	S_a [nm]	***S_y [nm]***	***S_q [nm]***	***S_a [nm]***	***S_y [nm]***	***S_q [nm]***	***S_a [nm]***	***S_y [nm]***	***S_q [nm]***
1	13,90	125,61	19,60	6,41	48,58	8,16	3,31	25,42	4,09
2	11,58	97,41	15,16	7,22	57,69	9,20	4,36	32,68	5,44
3	16,49	128,18	21,65	7,02	62,87	9,32	3,78	32,68	5,07
4	16,73	114,17	20,67	6,48	69,15	8,72	2,11	36,76	4,93
5	16,53	120,16	21,03	9,15	81,30	12,66	2,77	36,76	5,45
6	11,06	93,46	14,20	7,39	81,30	10,12	3,55	35,51	6,58
7	13,30	121,46	18,20	7,73	111,79	11,24	2,42	30,04	4,84
8	13,71	189,70	22,24	8,47	102,54	11,94	2,53	57,35	5,91
9	15,43	123,48	20,34	8,84	74,34	11,64	3,40	28,20	4,24
10	12,82	114,72	16,93	8,20	106,52	14,49	4,19	39,48	5,67
Average	**14,15**	**122,83**	**19,00**	**7,69**	**79,61**	**10,75**	**3,24**	**35,49**	**5,22**

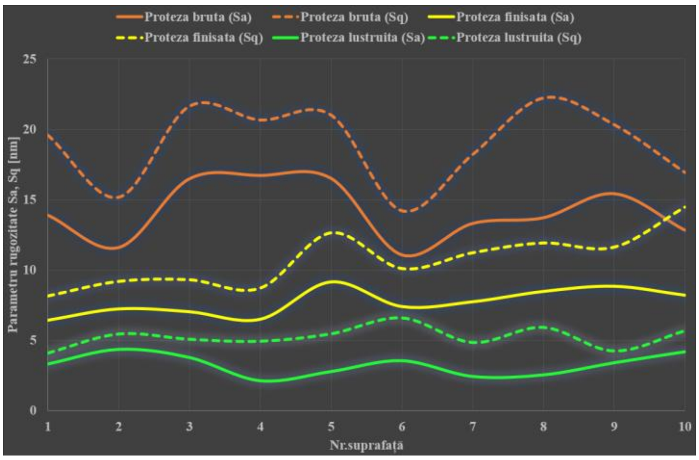


Fig. 34. Comparison of roughness parameters (S_a and S_q) established after determining the microtopography of surfaces

Considering that the roughness of the surfaces of dental prostheses influences the formation of bacterial plaque and other possible bacterial growths or other harmful microorganisms, but also that low roughness values contribute to the increase of important mechanical characteristics, this micro or nanometric study may be useful for evaluating the efficiency of the post-processing procedure and choosing the optimal finishing method to obtain appropriate results and to decrease the chance of negative biological or mechanical effects on the dental prosthesis and implicitly the patient.

For experimental researches in subchapter 7.3.5 on macrostructural analysis [188] of dental prostheses realized by selective laser melting, dental prostheses made by selective laser melting of two different materials were used: CoCrW-based alloy and NiCr-based alloy. In the case of metal or metal-ceramic prostheses, it is very important that the processing of metal surfaces be carried out in an appropriate way for several reasons: increasing wear resistance, chemical resistance and durability, decreasing electrolytic potential, improving mechanical properties and reducing surface micro-defects, improving the hygienic maintenance of dental prostheses and decreasing the adhesion of various microbial species to the surface of prostheses, increasing the adhesion of the aesthetic coating to the metal surface. For the study in this subchapter and to highlight the appearance of dental prostheses, three macroscopic magnifications were chosen for the stereomicroscope used - 6.3x, 10x and 15x.

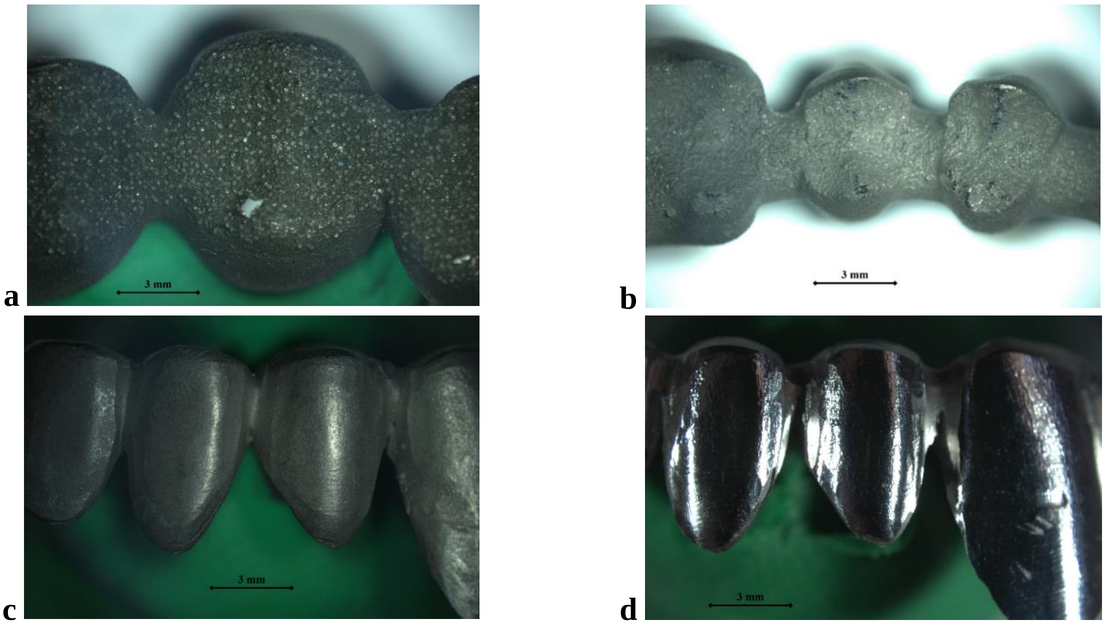


Fig. 35. Some results obtained regarding the macroscopic analysis of dental prostheses realized by selective laser melting in various stages of post-processing (15x magnifications): raw state - CoCr alloy (a) and NiCr alloy (b), finished (c) and polished (d)

Unlike microscopic examination, macroscopic analysis does not determine the details of the structure and is often a preliminary stage, not a final one of structural analysis. Macroanalysis can allow the selection of certain areas that require additional microscopic examination and important information can be obtained regarding: the quality of dental prostheses realized by selective laser melting in various stages of post-processing, the identification of certain defects such as structural discontinuity or chemical heterogeneity, preliminary study of the influence of finishing operations on the appearance of dental prostheses and choice of an area of interest for more advanced microscopic/microstructural investigations.

For the purpose of researches on energy-dispersive X-ray spectroscopy analysis of dental prostheses realized by selective laser melting in subchapter 7.4 I used the SEM/EDS Phenom ProX scanning electron microscopy system [195] [201]. In the elemental analysis of dental prostheses realized by selective laser melting I considered two different materials: based on cobalt - chromium and based on nickel – chromium alloys. Two dental crowns (polished CoCrW and pre-finished NiCr) were used to fit the dimensional limits of the microscope samples and it was desired to obtain SEM images and elemental analysis by dispersive X-ray spectroscopy of them in different areas. In total, for the selected region, a total of six points of interest were chosen for both dental crowns, desiring the chemical compositional evaluation for all six points of interest. Some results obtained from this research are shown in fig. 36-39.

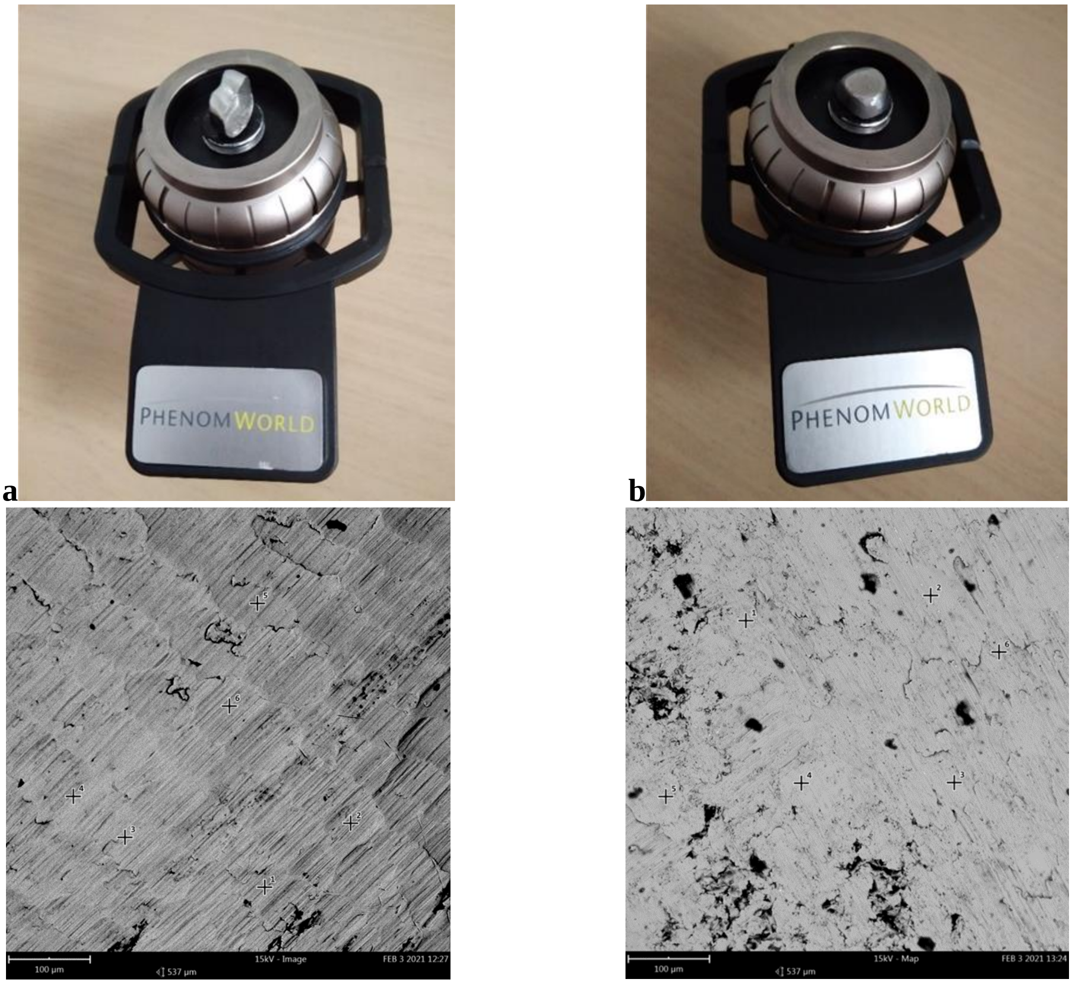


Fig. 36. Some results regarding the elemental analysis by dispersive X-ray spectroscopy of dental prostheses realized by selective laser melting: SEM images of dental prostheses from CoCr (a) and NiCr (b) with the areas of interest marked for elemental analysis by EDS spectroscopy, magnification 500x

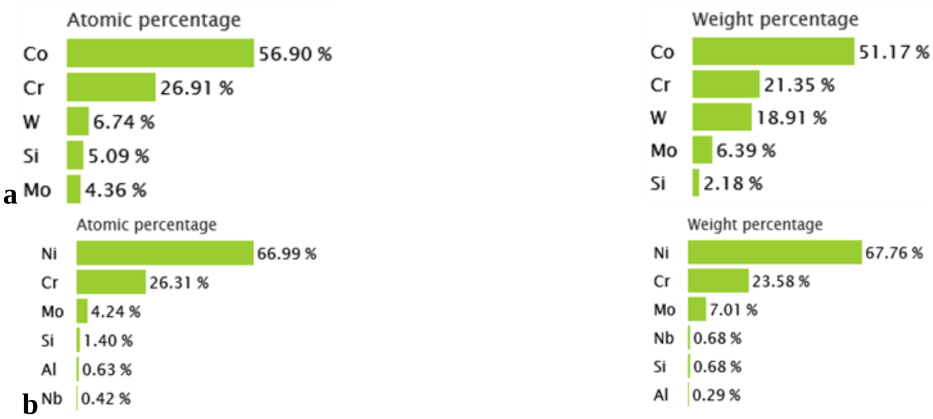


Fig. 37. Some results obtained on the atomic and mass percentage concentration for dental prostheses made by selective laser melting: CoCr (a) and NiCr (b)

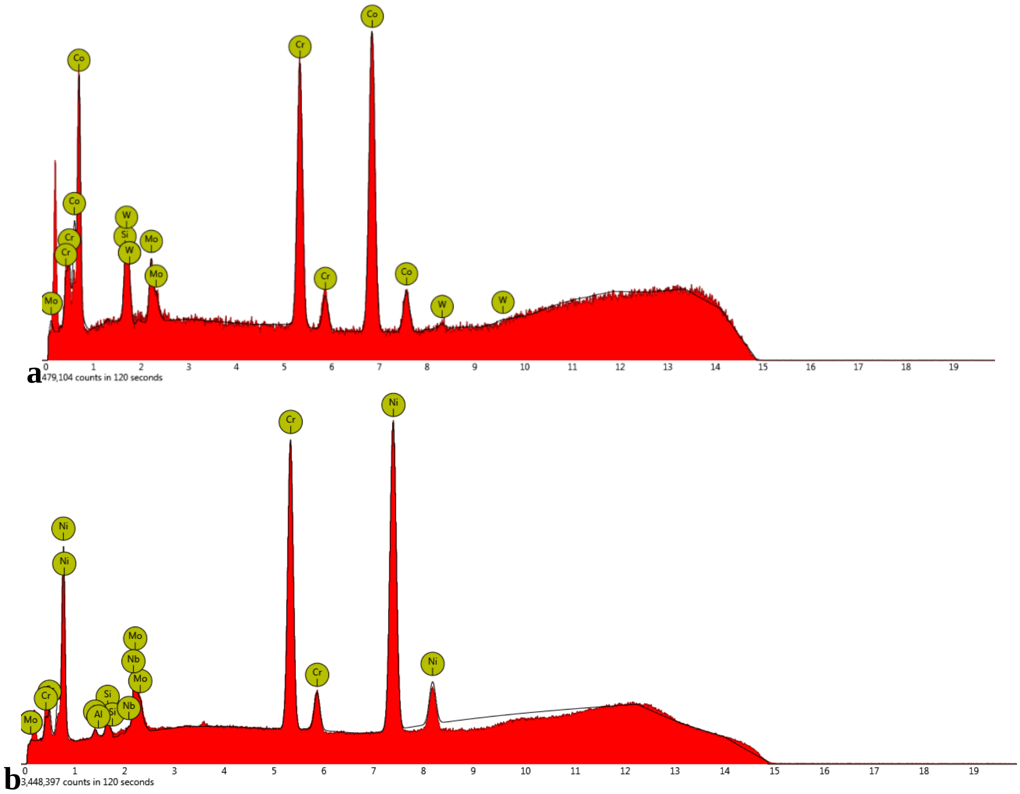


Fig. 38. Some results on EDS spectroscopic images obtained for areas of interest: CoCr (a) and NiCr (b)

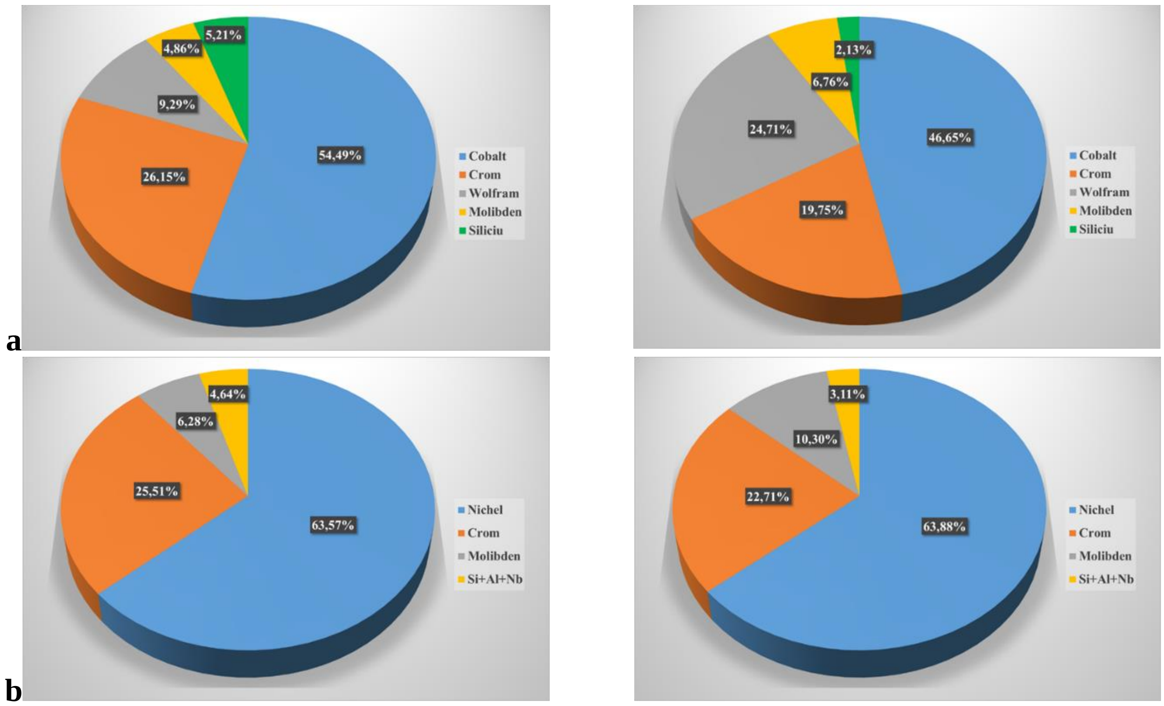


Fig. 39. Concentrația procentuală masică şi atomică medie determinată pentru proteza dentară din CoCr (a) şi NiCr (b)

In subchapter 7.5 I presented the results of experimental research on determining the hardness of dental prostheses realized by selective laser melting. The dental prostheses realized by selective laser melting was mechanically polished so that it could be tested for hardness. A total of five different surfaces were chosen and the hardness value resulting from the experimental determination was compared with the hardness values of this material made by traditional technologies.

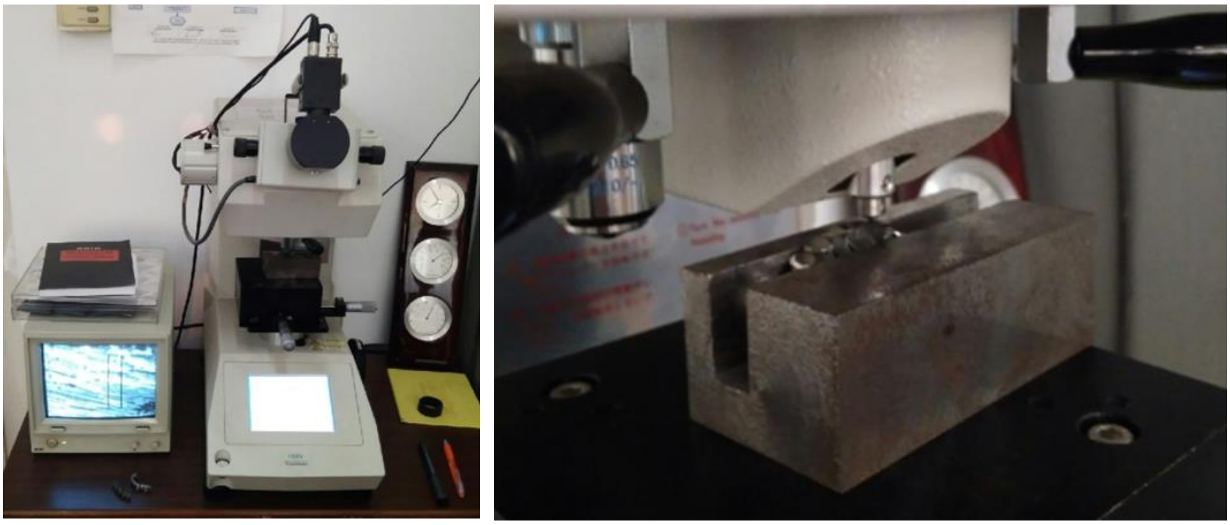


Fig. 40. Hardness test of dental prosthesis realized by selective laser melting

Fig. 41 presents some results of experimental research on the hardness test of dental prostheses realized by selective laser melting.

After this experimental research it can be concluded that dental prostheses realized by selective laser melting after polishing have an adequate hardness, considerably higher than the material to be replaced (enamel hardness - 275 HV). Moreover, all five determined hardness values exceed the hardness values for alloys with similar composition, but made by classical methods (below 450 HV) and the hardness values from the data sheet of the metal powder from which the dental prostheses was realized (485- 490 HV). Also, the values determined for hardness are close to those obtained by other researchers for alloys made by selective laser melting with similar chemical composition [205] [206] and and it is demonstrated that with the help of selective laser melting structures with a higher hardness than structures made of the same material are obtained, but by conventional casting or milling technologies. This is a major advantage for the performance over time of dental prostheses, and with the compensation of other deficiencies existing at this time, dental prostheses realized by selective laser melting will certainly be the first choice for dentists, patients, dental technicians or researchers [130].

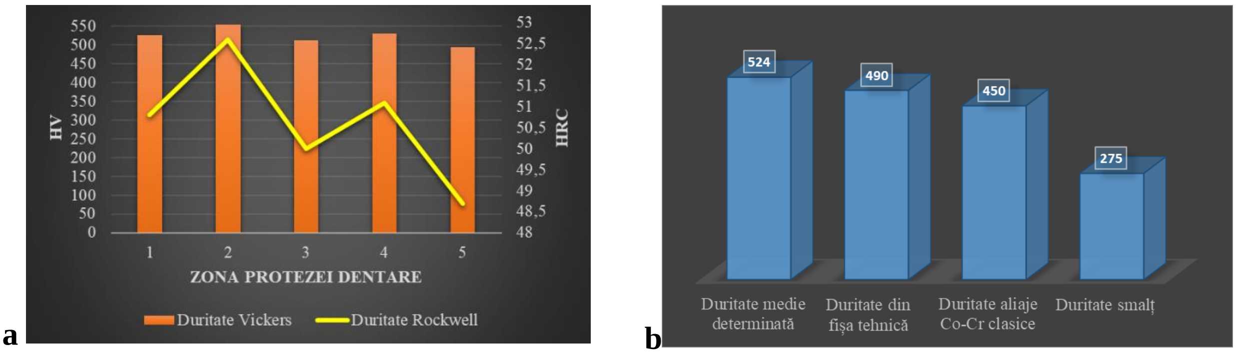


Fig. 41. Results of the experimental researches regarding the determination of the hardness of the dental prostheses realized by selective laser melting: a - the values of the determined hardness expressed in HV and HRC units for the dental prosthesis realized by selective laser melting; b - comparison of hardness values expressed in Vickers units for the average hardness of dental prostheses realized by selective laser melting, the hardness in the data sheet, the hardness of some classic alloys based on Co-Cr and the hardness of the enamel

CONCLUSIONS

C1 General conclusions

Additive technologies are of increasing interest in more and more fields, especially in the field of dental prosthetics due to the special advantages, and the researches in this doctoral thesis has highlighted this aspect. However, there are some disadvantages, but certainly these technologies will have a continuous direction of development and improvement and may soon become the first choice among dentists, dental technicians and patients in terms of technology for obtaining dental prostheses.

Following extensive documentation on issues related to dental anatomy and prosthetics, technologies for obtaining dental prostheses, properties of biocompatible materials used in dental prosthetics and additive technologies with applications in dental prosthetics, I have made several prostheses and dental prosthetic models from different materials using various computerized additive/subtractive technologies, different equipment and process parameters. Dental prostheses and dental prosthetic models realized by additive technologies from different materials have been characterized and analyzed from several points of view using modern and high-performance analysis equipment, softwares and systems, highlighting the advantages, disadvantages, processing and comparing the results obtained, being proposed some optimization solutions. Experimental researches have shown the advantage of dental prostheses realized by selective laser melting on some mechanical characteristics compared to dental prostheses realized by classical technologies. At the same time, experimental researches have shown and highlighted the importance of proper post-processing of dental prostheses realized by selective laser melting to achieve optimal and desired performance. I also performed numerical modeling on finite element analysis of dental structures obtained by digital intraoral scanning using several high-performance simulation software tools and mathematical modeling of the selective laser melting process, which could determine the thermal characteristics during the process of selective laser melting for several biometals used in dental prosthetics and the influence of process parameters on the thermal characteristics of the processed biometals was established.

Some of the results obtained from the researches were compared with the analytical or numerical results from the simulation or with the results obtained by other researchers. Also, some of the results obtained in this doctoral thesis have been published in specialized journals or held at international conferences. In total I have realized **40** scientific papers as first author or co-author (of which **12** have already been indexed ISI) and a book, specific to the doctoral topic, which can be found in the bibliography, but also in areas related to the doctoral thesis or other fields of mechanics and mechatronics, and some of the published works have already been cited by several researchers in prestigious international publications.

C2 Original contributions

In accordance with the objectives set for this doctoral thesis, among my own important and original contributions I would like to mention:

- ✓ Carrying out extensive research on issues related to the nature of dental anatomy and prosthetics, modern and current technologies for realizing dental prostheses (Ch. 1 and Ch. 2);
- ✓ Carrying out a research on biomaterials used in dental prosthetics and their properties, but also additive technologies with applications in dental prosthetics and their technological methods of post-processing proposing other possible applications of additive technologies in medicine and other fields (Ch. 3 and Ch. 4);
- ✓ Proposing and developing an original method of comparative analysis of dental prosthetic biomaterials depending on the main characteristics and essential factors,

which can more easily choose the appropriate material for each individual patient (Ch. 3.4);

- ✓ Obtaining dental prostheses and prosthetic dental models through several modern computerized additive and subtractive technologies: selective laser deposition, thermoplastic extrusion, vat photopolymerization and CAD-CAM milling. Different equipment, raw materials, software systems and process parameters were used for the realization, and the obtained structures, materials and equipment were characterized and compared, being identified analysis and optimization solutions. (Ch. 5.2, 5.3, 5.4, 5.5, 5.6);
- ✓ Numerical simulation by the finite element method of dental structures obtained through personalized digital intraoral scanning. Several advanced software tools were used to simulate and process digital files obtained by intraoral scanning, including the possibility of using advanced tools combined with anatomical CAD design and engineering CAE analysis programs (Ch. 5.7 și 5.8);
- ✓ Mathematical modeling of the selective laser melting process regarding heat transfer, as a result of which some thermal characteristics were obtained during the selective laser melting process for three biometals used to realize dental prostheses. The influence of important process parameters such as powder layer thickness, laser speed and power on the thermal characteristics during the selective laser melting process of some biometals used to realize dental prostheses was determined and the materials with the best properties were highlighted following mathematical modeling (Ch. 6.1 și Ch. 6.2);
- ✓ Carrying out an experimental study on testing at some mechanical loads the dental prosthetic models made by different additive technologies, materials and equipment. The experimental data were processed, highlighting the most suitable materials in terms of performance required. Some determined experimental data were compared with the results obtained from the simulation by the finite element analysis method (Ch. 7.1);
- ✓ Experimental determination of the most suitable materials for the realization of dental prosthetic models in terms of wear resistance (Ch. 7.2);
- ✓ Carrying out experimental research on the dimensional accuracy of additive technologies and equipment used to realize dental prosthetic models, identifying possible causes of dimensional errors (Ch. 7.3.1);
- ✓ Thermographic analysis of dental models realized by additive technologies and highlighting the way the structure cools after completion of construction (Ch. 7.3.2);
- ✓ Experimental determination of the thickness of the deposited layers for the materials used to realize dental prosthetic models using a high-performance multisensory measurement system. The experimental data obtained were processed and compared with the nominal value of the thickness of the layers set in the program, establishing the optimal material and equipment from this point of view (Ch. 7.3.3);
- ✓ Experimental establishment of nanoroughness and microtopography of the surfaces of dental prostheses realized by selective laser melting in different stages of post-processing using atomic force microscopy. It was highlighted how the post-processing operations influence the surface roughness at the microscale, establishing parameters such as arithmetic mean deviation, quadratic mean deviation, distance between the extremities of irregularities and comparing the results obtained (Ch. 7.3.4);
- ✓ Macroscopic analysis of dental prostheses realized by selective laser melting in different stages of post-processing (Ch. 7.3.5);
- ✓ Experimental determination of the chemical composition of the alloys used for dental prostheses made by selective laser melting using elemental analysis by X-ray dispersive spectroscopy. SEM images and EDS spectroscopic images were obtained for the surfaces of dental prostheses, determining the mass and atomic percentage

concentration for two different alloys used to realize dental prostheses by selective laser melting (Ch. 7.4);

- ✓ Experimental determination of the hardness of dental prostheses realized by selective laser melting after the polishing operation. The obtained results were compared with the hardness values specified in the alloy data sheet and with the hardness values for structures made by classical methods of alloys with similar chemical composition, but also with the results of hardness determinations made by other researchers for structures realized by selective laser melting alloys with similar chemical composition (Ch. 7.5).

C3 Perspectives on the development of researches for dental prosthesis technologies in the future

Analyzing the results obtained in the researches conducted in this doctoral thesis, were contoured several possible directions and perspectives on the development of further research for dental prosthesis technologies, including the following:

- Further research on other materials that can be used as raw material for the execution of dental prostheses and dental prosthetic models through additive technologies, including ceramic materials;
- Carrying out additional research on the optimal printing and post-processing conditions for dental prosthetic applications in order to obtain restorations and dental prosthetic models with improved properties;
- Realization of dental prosthetic models through other additive technologies such as binder jetting or material jetting, as well as the evaluation of their physical and mechanical characteristics;
- Carrying out research on the production of dental prostheses by other metal additive technologies – electron beam melting and direct energy deposition;
- Extension of research on the properties and characteristics of dental prostheses realized by selective laser melting and other additive technologies compared to dental prostheses realized by conventional manufacturing methods;
- Carrying out research on some mechanical tests for dental prostheses realized by selective laser melting and other additive technologies;
- Carrying out specific biocompatibility and cytotoxicity tests for dental prostheses realized by selective laser melting and classical technologies from various materials;
- Study of the action of some fluids and biofluids on the performances of dental prostheses realized by additive technologies;
- Deepening simulations by the finite element method for complex dental prosthetic structures using advanced analysis software systems;
- Carrying out additional research on mathematical modeling and numerical simulation for some additive manufacturing technologies using specific analysis software environments;
- Development of experimental research on finishing by electrochemical polishing of dental prostheses realized by selective laser melting and study of the characteristics of electropolished dental prostheses compared to dental prostheses finished by classical mechanical methods.

SELECTIVE BIBLIOGRAPHY
(extracted from a total of 206 references)

[4] Berkowitz B., Holland G., Moxham B., Oral Anatomy, Histology and Embriology, Edited by Mosby, 2009;

[6] Anselm Wiskott H.W., Fixed Prosthodontics. Principles and clinics. Quintessence Publ., 2011;

[10] Fernandes N.A., Vally Z.I., Sykes L.M., The longevity of restorations - a literature review, SADJ, vol.70, no.9, pp.410-413, 2015;

[11] Carlsson G.E., Success and Failure of Different Types of Crowns and Fixed Dental Prostheses, JPPA, vol.2(1), pp.24-32, 2014;

[15] Shillingburg H.T. et al, Fundamentals of fixed prosthodontics, Fourth edition, Quintessence Publishing Co, Inc;

[31] **E.Moraru**, O.Donțu, A.Petre, D.Vaireanu, F.Constantinescu, D.Besnea, Some technological particularities on the execution of dental prostheses realized by selective laser deposition, Journal of Optoelectronics and Advanced Materials, vol.20, no.3-4, pp.208-213, 2018;

[51] T. Miyazaki, Y.Hotta, CAD/CAM systems available for the fabrication of crown and bridge restorations. Aust Dent J, vol.56, pp.97-106, 2011;

[55] U. ben Irfan, K.Aslam, R.Nadim, A Review On Cad Cam In Dentistry, J Pak Dent Assoc, vol.24(3): 112116;

[56] J.P.Kruth, X.Wang, T.Laoui, L.Froyen, Lasers and materials in selective laser sintering, Assembly Automation, vol. 23(4), pp. 357-371, 2003;

[57] Dontu O., Tehnologii de prelucrat cu laser, Ed. Tehnică, 1985, Bucuresti;

[58] A.Tathe, M.Ghodke, A.P.Nikalje, A brief review: Biomaterials and their applications, International Journal of Pharmacy and Pharmaceutical Sciences, vol.2, pp.19-23, 2010;

[59] N.R.Patel, P.P.Gohil, A Review on Biomaterials: Scope, Applications &Human Anatomy Significance, International Journal of Emerging Technology and Advanced Engineering, vol.4(2), pp.91-101, 2012;

[61] V.Saenz de Viteri, E.Fuentes, Titanium and Titanium Alloys as Biomaterials, In: Jrgen Gegner (Eds.), Tribology - Fundamentals and Advancements, 2013;

[66] M.J. Tyas, Dental materials science – the maintenance of standards, J Oral Rehabil., vol.18, no.2, pp.105-110, 1991;

[70] K.J.Chun, H.H.Choi, J.Y.Lee, Comparison of mechanical property and role between enamel and dentin in the human teeth, J Dent Biomech, vol.5, 2014;

[82] D.Besnea, O.Dontu, **E.Moraru**, E.Dinu, Tehnologii aditive cu aplicații în mecatronică. Construcție și exploatare, Editura Printech, 2019, București.

[89] S.Negi, R.K.Sharma, Basics, applications and future of additive manufacturing technologies: A review, Journal of Manufacturing Technology Research, vol.5, pp.75-96, 2013.

[90] D.Besnea, O.Dontu, V.Constantin, A.Spanu, C.Rizescu, **E.Moraru**, Applications of additive technologies in the food industry, International Journal of Mechatronics and Applied Mechanics, vol.3, pp.245-248, 2018;

[93] D.Besnea, **E.Moraru**, O. Dontu, V.Constantin, A.Spanu, R.Ciobanu, Research on the realization of anatomical models by additive technologies, International Journal of Modeling and Optimisation, vol.8, no.4, pp.208-211, 2018;

[96] N.N.Kumbhar, A.V.Mulay, Post Processing Methods used to Improve Surface Finish of Products which are Manufactured by Additive Manufacturing Technologies: A Review, J. Inst. Eng. India Ser. C vol. 99(4) pp.481–487, 2018;

[97] **E.Moraru**, D.Besnea, O.Dontu, G.I. Gheorghe, V.Constantin, Applications of Additive Technologies in Realization of Customized Dental Prostheses, International Journal of

Mechatronics and Applied Mechanics, vol.3, pp.66-71, 2018;
[98] **E.Moraru**, O.Dontu, D.Besnea, V.Constantin, Study and realization of prosthetic dental models by additive technologies, IOP Conf. Ser.: Mater. Sci. Eng. 444 042017, 2018;
[100] P.Berce, N.Balc, C.Caizar, R.Pacurar, A.Radu, S.Bratean, I. Fodorean, Tehnologii de fabricatie prin adaugare de material si aplicatiile lor (Bucuresti: Editura Academiei Romane), 2014;
[102] J-P. Kruth, P. Mercelis, J. Van Vaerenbergh, L. Froyen and M. Rombouts, Binding mechanisms in selective laser sintering and selective laser melting, Rapid Prototyping Journal, vol.11, no.1, pp.26-36, 2005;
[110] Dontu O., Tehnologii și sisteme integrate de fabricație pentru mecatronică, Editura Printech, 2009, Bucuresti;
[115] **E.Moraru**, O.Dontu, D.Besnea, C.Rizescu, D.Rizescu, V.Constantin, Theoretical and numerical researches on the electrochemical polishing of dental prostheses realized by selective laser melting, IOP Conf. Ser.: Mater. Sci. Eng. 564 012029, 2019;
[122] D.Besnea, O.Dontu, **E.Moraru**, C.Rizescu, G.I.Gheorghe, E.Dinu (2020) Constructive Solution for Multi-filament 3D Printing. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2019. ICOMECYME 2019. Lecture Notes in Networks and Systems, vol 85. Springer, Cham;
[125] **E.Moraru**, D.Besnea, A.Spanu, V.Constantin, Experimental research on some modern technologies and materials applied in prosthetic dentistry, Journal of Engineering Sciences and Innovation,vol.3, Iss.4, pp.329-338, 2018;
[130] **E.Moraru**, O.Dontu, C.Rizescu, A.Spanu, R.Ciobanu, C.Draghici, Laser-assisted additive technologies for the execution of dental restorative prostheses, IOP Conf. Ser.: Mater. Sci. Eng. 997 012050, 2020;
[139] **E.Moraru**, O.Dontu, A.Spanu, D.Prisecaru, C.Draghici, Some considerations regarding the use of vat photopolymerisation technique in prosthodontics, International Journal of Mechatronics and Applied Mechanics, Iss.6, Vol.I, pp.87-90, 2019;
[141] A.N.Natali, Dental biomechanics, Editura Taylor&Francis, New York, 2003;
[143] L.B.Durand, J.C.Guimaraes, S.Monteiro Junior, L.N.Baratieri, Modeling and validation of a 3D premolar for finite element analysis, Rev Odontol UNESP, vol.45, no.1, pp.21-26, 2016;
[151] Materialise Mimics software, https://www.materialise.com/en/medical/mimics-innovation-suite/mimics;
[152] Ansys software, https://www.ansys.com/;
[153] D. Rosenthal, The Theory of Moving Sources of Heat and Its Application to Metal Treatments, Transactions of the ASME, 68, pp. 849-866, 1946;
[155] P.Bajaj, SLM Manufacturing of Molybdenum, Disertation, University of Sheffield, 2016;
[158] L.Shpakova, G.I.Gheorghe, C.Nitu, O.Dontu O, **E.Moraru**, D.Besnea, D.Dragomir (2020) Thermal Analysis of Some Prosthetic Dental Biomaterials Processed by Selective Laser Melting. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2019. ICOMECYME 2019. Lecture Notes in Networks and Systems, vol 85. Springer, Cham
[159] C. A. Boley, S. C. Mitchell, S. Rubenchik, S. S. Q. Wu, Metal powder absorptivity: modeling and experiment, Applied Optics, vol.55, no.23, 2016;
[162] P.A.Hooper, Melt pool temperature and cooling rates in laser powder bed fusion, Additive manufacturing, vol.22, pp.548-559, 2018;
[165] Test Stand HV-500N Imada, https://www.hans-schmidt.com/;
[166] **E.Moraru**, O.Dontu, D.Besnea, C.Rizescu, D.Rizescu, A.Popescu-Cuta, Experimental researches regarding mechanical behaviour of dental prototypes realized by additive technologies, MATEC Web of Conferences, vol. 290, Pages 03011, 2019;
[167] **E.Moraru**, O.Dontu, C.Rizescu, D.Rizescu, Comparative study and mechanical

analysis of some additive manufactured dental models, 8th International Conference on Materials Science and Technologies – RoMat 2020, Bucharest, Romania, November 26-27th, 2020;

[171] D. Besnea, C.Rizescu, **E.Moraru**, E.Dinu, I.Panait, Comparative study regarding the wear of gearwheels manufactured through additive technologies, MATEC Web of Conferences, vol.290, Pages 08001, 2019;

[173] E.George, P.Liacouras, F.J.Rybicki, D.Mitsouras, Measuring and Establishing the Accuracy and Reproducibility of 3D Printed Medical Models, Radiographics, vol.37(5), p. 1424–1450, 2017;

[175] **E.Moraru**, M.F.Stefanescu, O.Dontu, C.Rizescu, C.Draghici, Thermographic Analysis of 3D Printed Dental Models. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber- MixMechatronics - 2020. ICOMECYME 2020. Lecture Notes in Networks and Systems, vol 143. Springer, Cham;

[181] E.R.Baciu, N.C.Forna, Influența tehnicilor de finisare asupra rugozității suprafețelor componentelor metalice ale restaurărilor protetice, Rev. Med. Chir. Soc. Med. Nat., vol.114, nr.4, 2010, Iași, pp.1198-1203;

[182] V.L. Mironov, Fundamentals of Scanning Probe Microscopy, The Russian Academy of Science, Nizhniy Novgorod, 2004;

[188] O.I.Vaulina, Metode de cercetare macroscopică pentru metale și aliaje (in rusă), Universitatea Politehnica din Tomsk, Institutul de fizica tehnologiilor avansate, 2015;

[195] D.Shindo, T.Oikawa, Energy Dispersive X-ray Spectroscopy, In: Analytical Electron Microscopy for Materials Science. Springer, Tokyo, 2002;

[201] J.Goldstein, D.Newbury, D.Joy, C.Lyman, P.Echlin, E.Lifshin, L.Sawyer, J.Michael, Scanning Electron Microscopy and X-ray Microanalysis, Third Edition, Springer, New York, 2003;

[205] N.A.Dolgov, T.Dikova, D.Dzhendov, D.Pavlova, M.Simov, Mechanical properties of dental Co-Cr alloys fabricated via casting and selective laser melting, Scientific Proceedings II International Scientific-Technical Conference "Innovations in Engineering", pp.29-33, 2016;

[206] Y.Lu, S.Wu, Y.Gal, J.Li, C.Zhao, D.Zhuo, J.Lin, Investigation on the microstructure, mechanical property and corrosion behavior of the selective laser melted CoCrW alloy for dental application, Mater Sci Eng C Mater Biol Appl, vol.49, pp.517-525, 2015;

LIST OF PUBLISHED WORKS

The researches carried out during the doctoral studies were disseminated by publishing several articles in specialized journals indexed by ISI, BDI and other international databases and participating at international conferences in the field. In addition to the published scientific papers associated with the topic of doctoral studies, which are also found in the bibliography of the doctoral thesis, I have done other papers in fields related to the doctoral thesis or other fields of mechanics and mechatronics. Below are all the scientific publications realized as the first author or co-author during doctoral studies.

ISI indexed scientific papers

1. **E. Moraru**, O. Dontu, A. Petre, D. Vaireanu, F. Constantinescu, D. Besnea, Some technological particularities on the execution of dental prostheses realized by selective laser deposition, Journal of Optoelectronics and Advanced Materials, Vol.20, No 3-4, March-April 2018, pp.208-213;
2. **E. Moraru**, O. Dontu, D. Besnea, V. Constantin, Study and realization of prosthetic dental models by additive technologies, IOP Conf. Ser.: Mater. Sci. Eng. 444 042017, 2018;
3. D. Besnea, C.I. Rizescu, D. Rizescu, D. Comeaga, R. Ciobanu, **E. Moraru** - Study of deflection behaviour of 3D printed leaf springs, IOP Conf. Ser.: Mater. Sci. Eng. 444 042008, 2018;
4. **E. Moraru**, O. Dontu, D. Besnea, C. Rizescu, D. Rizescu, V. Constantin, Theoretical and numerical researches on the electrochemical polishing of dental prostheses realized by selective laser melting, IOP Conf. Ser.: Mater. Sci. Eng. 564 012029, 2019;
5. **E. Moraru**, O. Dontu, D. Besnea, C. Rizescu, D. Rizescu, A. Popescu-Cuta, Experimental Researches Regarding Mechanical Behaviour of Dental Prototypes realized by Additive Technologies, MATEC Web of Conferences, Volume 290, Pages 03011, 2019;
6. N. Baran, M. Constantin, B. Tănase, **E. Moraru**, C. I. Moga, Influence of fine bubble generator architecture on time variation of dissolved oxygen concentration in water, Revista de Chimie, 70(6), pp. 2132-2135, 2019;
7. D. Besnea, E. Dinu, **E. Moraru**, A. Spanu, C. Rizescu, V. Constantin, Experimental researches regarding the manufacturing of new thermoplastic materials used in additive technologies, Materiale Plastice, 56(1), pp. 167-170, 2019;
8. Rizescu C.I., Besnea D., Rizescu D., **Moraru E.**, Constantin V. (2019) Mechanical Analysis of Leaf Springs Realized by Additive Technologies. In: Trojanowska J., Ciszak O., Machado J., Pavlenko I. (eds) Advances in Manufacturing II. Lecture Notes in Mechanical Engineering. Springer, Cham;
9. D. Prisecaru, D. Besnea, **E. Moraru**, S. Cananau, Additive Manufactured Bioplastics for Conceptual Models of Knee Customized Prostheses, Revista Materiale Plastice, Vol.56, No.4, pp.957-963, 2019;
10. M. Selagea, **E. Moraru**, D. Besnea, R. Udrea, B. Lungu, Some technological aspects regarding laser ablation of oxides resulting from exposing alloyed steels to high temperatures, Optoelectroniscs and Advanced Materials – Rapid Communications, Vol.13, No.9-10, pp.539-545, 2019;
11. D. Besnea, C. Rizescu, **E. Moraru**, I. Panait, D. Rizescu, I. Dinu, Using of additive technologies in fabrication of casting models, IOP Conf. Ser.: Mater. Sci. Eng. 564 012016, 2019;
12. D. Besnea, C. Rizescu, **E. Moraru**, E. Dinu, I. Panait, Comparative study regarding the wear of gearwheels manufactured through additive technologies, MATEC Web of Conferences, Volume 290, Pages 08001, 2019.

BDI indexed scientific papers

1. **Moraru E.**, Besnea D., Dontu O., Gheorghe G.I., Constantin V. (2019) Applications of Additive Technologies in Realization of Customized Dental Prostheses. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2018. ICOMECYME 2018. Lecture Notes in Networks and Systems, vol 48. Springer, Cham;
2. Besnea D., Dontu O., Constantin V., Spanu A., Rizescu C., **Moraru E**. (2019) Applications of Additive Technologies in the Food Industry. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2018. ICOMECYME 2018. Lecture Notes in Networks and Systems, vol 48. Springer, Cham;
3. Dontu O., Ioana M.C., Tănase B., Băran N., Gheorghe G.I., **Moraru E.** (2019) Researches Regarding the Use of Additive Technologies in the Construction of Water Aeration Elements. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2018. ICOMECYME 2018. Lecture Notes in Networks and Systems, vol 48. Springer, Cham;
4. Besnea D., Rizescu D., Rizescu C., Dinu E., Constantin V., **Moraru E.** (2019) Additive Technologies and Materials for Realization of Elastic Elements. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2018. ICOMECYME 2018. Lecture Notes in Networks and Systems, vol 48. Springer, Cham;
5. D. Rizescu, D. Besnea, C. I. Rizescu, **E. Moraru**. Study behavior of Geneva mechanism using 3D printing technology, IOP Conf. Ser.: Mater. Sci. Eng. 514 012032, 2018;
6. **E. Moraru**, M. Selagea. Design, modeling and simulation of thermal microactuators. U.P.B. Sci. Bull., Series D, Vol.80, Iss.3, pp.19-30, 2018;
7. D. Besnea, G. I. Gheorghe, O. Dontu, **E. Moraru**, V. Constantin, I. C. Moga, Experimental researches regarding realization of wastewater treatment elements by means of modern technologies, International Journal of Mechatronics and Applied Mechanics, Issue 4, pp.61-65, 2018;
8. I.C. Moga, O.G. Donţu, N. Băran, D. Besnea, **E. Moraru**, G. Petrescu, Aeration system to be used in wastewater treatment, IOP Conf. Ser.: Mater. Sci. Eng. 572 012105, 2019;
9. Besnea D., Dontu O., **Moraru E.,** Rizescu C., Gheorghe G.I., Dinu E. (2020) Constructive Solution for Multi-filament 3D Printing. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2019. ICOMECYME 2019. Lecture Notes in Networks and Systems, vol 85. Springer, Cham;
10. Shpakova L., Gheorghe G.I., Nitu C., Dontu O., **Moraru E.,** Besnea D., Dragomir D. (2020) Thermal Analysis of Some Prosthetic Dental Biomaterials Processed by Selective Laser Melting. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2019. ICOMECYME 2019. Lecture Notes in Networks and Systems, vol 85. Springer, Cham;
11. **Moraru E.,** Besnea D., Dontu O., Gheorghe G.I., Moga I.C., Popescu G.E. (2020) Fabrication Technologies of Aeration Systems for the Ecological Treatment of Wastewater. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics – 2019. ICOMECYME 2019. Lecture Notes in Networks and Systems, vol 85. Springer, Cham;
12. **E. Moraru**, O. Dontu, A. Spanu, D. Prisecaru, C. Draghici, Some considerations regarding the use of vat photopolymerisation technique in prosthodontics, International Journal of Mechatronics and Applied Mechanics, Iss.6, Vol.I, pp.87-90, 2019;
13. A. Spanu, D. Besnea, **E. Moraru**, The suspension system with pressure control used for lower limb prostheses, International Journal of Mechatronics and Applied Mechanics, Iss.6, Vol.II, pp.15-18, 2019;
14. M. Dascalu, D. Dragomir, D. Besnea, L. Dobrescu, A.M. Pascalau, D. Dobrescu, E. Franti, **E. Moraru**, A. Plavitu, Mechatronic structure for forearm prosthesis with artificial skin, Smart Innovation, Systems and Technologies 174, pp. 471-481, 2020;

15. Dinu E., Besnea D., Ping A.S., Spanu A., **Moraru E.,** Panait I. (2020) Device for Injection Molding Realized by Additive Technologies. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber- MixMechatronics – 2020, Lecture Notes in Networks and Systems, vol 143. Springer, Cham;
16. Spânu A.R., Besnea D., **Moraru E**. (2020) The Dynamic Modeling of Ball and Plate Mechatronic System with Two Simultaneously Degrees of Freedom. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber- MixMechatronics – 2020, Lecture Notes in Networks and Systems, vol 143. Springer, Cham;
17. **E. Moraru**, M.F. Stefanescu, O. Dontu, C. Rizescu, C. Draghici, Thermographic Analysis of 3D Printed Dental Models. In: Gheorghe G. (eds) Proceedings of the International Conference of Mechatronics and Cyber- MixMechatronics - 2020. Lecture Notes in Networks and Systems, vol 143. Springer, Cham;
18. **E. Moraru**, O. Dontu, C. Rizescu, A. Spanu, R. Ciobanu, C. Draghici, Laser-assisted additive technologies for the execution of dental restorative prostheses, IOP Conf. Ser.: Mater. Sci. Eng. 997 012050, 2020;
19. D. Besnea, M. Avram, S. Cananau, **E. Moraru**, A. Spanu, V. Constantin, I. C. Panait, Constructive and functional particularities of 3D printers with applications in the food industry, IOP Conf. Ser.: Mater. Sci. Eng. 997 012036, 2020;
20. D. Besnea, E. Dinu, C. Rizescu, **E. Moraru,** D. Rizescu, N. Baran, T. Pascu, I.C. Panait, Experimental stand for studying the stretch behaviour of woven plastic nets used in the food industry, IOP Conf. Ser.: Mater. Sci. Eng. 997 012037, 2020;
21. **E. Moraru**, O. Dontu, N. Baran, A. Petre, C.I. Moga, Experimental researches regarding the depollution of wastewater by forced oxygenation and ozonation, Revista de Chimie, Nr.9 (1), pp.202-209, 2020;
22. G. Ionașcu, E. Manea, R. Gavrilă, **E. Moraru,** Perspectives on the use of thin films technologies in precision mechanics and mechatronics, International Journal of Mechatronics and Applied Mechanics, Issue 8, Vol. II, pp.204-208, 2020;
23. **E. Moraru**, O. Dontu, C. Rizescu, D. Rizescu, Comparative study and mechanical analysis of some additive manufactured dental models, 8th International Conference on Materials Science and Technologies – RoMat 2020, Bucharest, Romania, November 26-27th, 2020, lucrare susţinută la conferinţă (în curs de publicare).

Other publications

1. D. Besnea, **E. Moraru**, O. Dontu, V. Constantin, A.Spanu, R.Ciobanu - Research on the realization of anatomical models by additive technologies, International Journal of Modeling and Optimisation, Vol.8, No.4, pp.208-211, 2018;
2. **E. Moraru**, D. Besnea, A. Spanu, V. Constantin, Experimental research on some modern technologies and materials applied in prosthetic dentistry, Journal of Engineering Sciences and Innovation, Vol.3, Iss.4, pp.329-338, 2018;
3. D. Besnea, O. Donțu, **E. Moraru**, E.Dinu, Tehnologii aditive cu aplicații în mecatronică. Construcție și exploatare (carte), Editura PRINTECH, Bucureşti, 2019;
4. C.I. Moga, **E. Moraru**, O. Dontu, D. Besnea, B.I. Doroftei, A. Isitman, G. Petrescu, Innovative technological solutions for efficient biological wastewater treatment, Annals of the Faculty of Engineering Hunedoara, Vol.18 (4), pp.181-186, 2020;
5. Stoican (Prisecaru) M.M, Băran N., Besnea D., **Moraru E.,** A constructive solution for a rotating machine with profiled rotors that transport fluids, Fiability & Durability / Fiabilitate si Durabilitate, Issue 1, p.194-203, 2020;
6. Gheorghe V., **Moraru E.,** Shpakova L., Kinematic chain elements effect on the design of robot manipulators drive control systems, Proceedings of the International scientific and practical online conference "Integration of Science, education and production as the basis for implementation of the Nation Plan" (Saginov's readings No. 12), June 18-19, 2020, Karaganda State Technical University.