MEDICAL UNIVERSITY – VARNA
“PROF. DR. PARASKEV STOYANOV”

FACULTY OF DENTAL MEDICINE

DEPARTMENT OF DENTAL MATERIALS SCIENCE AND PROPAEDEUTICS OF PROSTHETIC DENTAL MEDICINE

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3D PRINTED PROTOTYPES OF CAST METAL DENTURE FRAMEWORKS FABRICATED BY LASER STEREOLITHOGRAPHY PRINTER

DISSERTATION SUMMARY

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Scientific Supervisor:
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The thesis consists of 142 pages and is illustrated with 4 tables and 78 figures. The bibliography includes 180 sources, as 26 of them are in Cyrillic and 164 - in Latin.

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The materials for the defense of the dissertation are available at the Library of Medical University - Varna and are published at the website of MU-Varna.

CONTENTS

ABBREVIATIONS

PMMA – Polymethyl methacrylate

ADA – American Dental Association

ASTM - American Society for Testing and Materials

CAD – Computer Aided Design

CAD/CAM – Computer Aided Design / Computer Aided Manufacturing

DLP-SLA – Digital Light Projection Stereolithography

FDM – Fused Deposition Modeling

IJP – Inkjet Printing

LCD – Liquid Crystal Display

LED – Light-emitting Diode

LFS – Low Force Stereolithography

MSLA – Masked Stereolithography

SEBM – Selective Electron Beam Melting

SLA – Stereolithography

SLM – Selective Laser Melting

SLP – Selective Laser Polymerization

SLS – Selective Laser Sintering

INTRODUCTION

A relatively new direction for development of dental medicine are the additive technologies. According to American Society for Testing and Materials (ASTM) the additive manufacturing is defined as: “The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.” An important characteristic of the additive manufacturing technology is the provided opportunity for fabrication of details with complex configuration of their surface and core. In addition, it allows simultaneous fabrication of huge number of details. Thereby the additive manufacturing saves time and allows fabrication of intricate objects. The additive manufacturing in dental medicine is used for fabrication of dentures, denture prototypes, which should be cast, or models, which are used for further denture manufacturing.

One of the most commonly used additive manufacturing method, also in dentistry, is the stereolithography. This technology has been well known for four decades, but there are fundamental issues that still remain unsolved. In addition, the contemporary dental practice tries to the integrate this new approach into the conventional methods for denture fabrication. Therefore, the aim of the presented scientific research is to improve the conditions for fabrication of cast metal dentures using 3D printed prototypes, manufactured by laser stereolithography printer and also to improve the casting conditions by integration of innovative methods of fabrication in practice.

CHAPTER ONE

AIM AND TASKS OF THE SCIENTIFIC RESEARCH

AIM:

The aim of the scientific research is to explore the manufacturing opportunities for fabrication of cast metal dentures by 3D printed prototypes by laser stereolithography printer.

In order to be achieve the main purpose of the study, the following tasks should be explored:

TASKS:

1. Comparative study of the temperature related physical changes and the presence of residual ash content of different materials used for fabrication of patterns (by milling, CAD/CAM and SLP) for casting from dental alloys.

1.1. Comparative study of the temperature related physical changes of different materials for fabrication of patterns (by milling, CAD/CAM and SLP) for casting from dental alloys.

1.2. Comparative study of the presence and the amount of the residual ash remnants of the examined patterns after burnout.

2. Evaluation of the production accuracy of objects made by SLP 3D printing technology.

2.1. Comparative study of 3D printing accuracy of objects with different orientation during the production process, while two types castable resins are observed.

2.2. Comparative study of the 3D printing accuracy, when objects with different structure are fabricated of Castable Resin® and Castable Wax®

2.3. Evaluation of the influence of the post-curing process to the 3D printed objects of Castable Resin®.

3. Study of the effect of different structural configurations of 3D printed objects, made of Castable Resin® and Castable Wax®, to the casting mold preparation process, while different temperature rates and investment materials are used.

4. Casting conditions improvement by software optimization of 3D printed patterns designed for casting dental alloys.

4.1. Casting conditions improvement by digital planning and 3D printing of crown patterns and a custom-made sprue system together as a single object.

4.2. Casting conditions improvement by digital planning and 3D printing of crown patterns, custom-made sprue system, casting ring and casting cone together as a single object.

CHAPTER TWO

MATERIALS AND METHODS

In order to be explored the tasks of the research, the following materials and methods are used.

Materials and Methods Used for the Purpose of the Study of Task 1.

The offered materials for pattern fabrication by Formlabs ™, for Form 2® 3D printer, can be used for cast metal objects production by conversion of a preliminary denture model. Some of the most important factors that affect this process are the temperature related physical changes of the patterns and the presence of residual ash remnant after the burnout process.

For the purpose of the study of **task 1.1** four identical objects were prepared from the following materials: Pattern Resin LS™ (GC™), C-cast (KaVo Dental ™), CAD/CAM wax (Yeti Dental™), Castable Resin® FLCABL02 (Formlabs™).

A silicon mold with the shape of cylinder with base of 2 centimeters in diameter and a height of 2 centimeters was used to be filled with a Pattern resin LC® (GC™), and was let to cure. A corresponding STL-file for the same size cylinder was used to get two other cylinders, milled from C-cast® (KaVo™ Dental), and CAD/CAM wax (Yeti Dental™). The fourth identical cylinder was 3D printed by SLP technology from Castable Resin® FLCABL02 (Formlabs™) as a solid object. And prior to heating was post cured at 60 ºC for 240 min in Formcure® (Formlabs™). **Fig.1.**

Fig.1. *The examined samples are shown, from left to right as follows: CAD/CAM wax (Yeti Dental™), C-cast® (KaVo Dental™), Pattern resin LC® (GC™), and Castable Resin® (Formlabs™).*

A pot from investment material Sherafina® Rapid (SHERA™) was poured and the objects were aligned into it and were inserted into the heating furnace for casting (Miditherm® 100 MP, BEGO™) at 25°C. The temperature rate is as shown on **fig.2.**

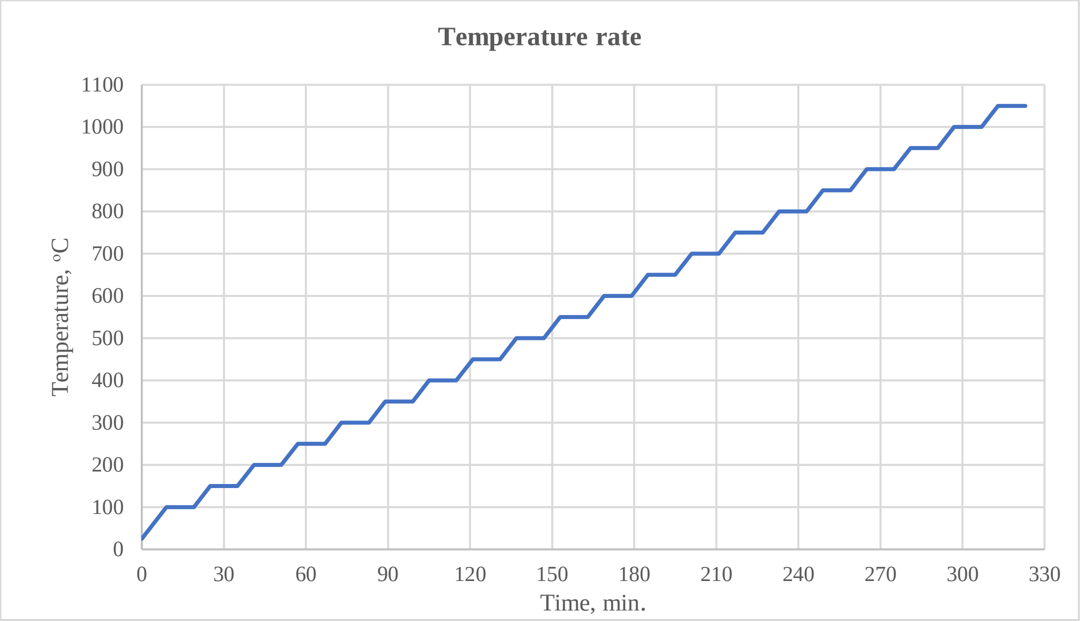


Fig.2. *Temperature/time chart.*

According to the temperature rate the pot is inserted at 25°C and the temperature is raised to 100°C, then a 10 min. hold is presented. After that the temperature is raised to 150°C and hold for 10 min again. The same pattern is repeated till 1050°C is reached. A comparison of the main temperature related physical and volumetric changes of the samples are made during different stages of the experiment.

For the purpose of the study of **task 2.2** the refractory pot is removed from the furnace after the 1050°C is reached. Then it is left to cool down. The residual ash remnant of each object is collected and explored by an analytical balance.

Materials and Methods Used for the Purpose the Study of Task 2.

The accuracy of 3D printing process, may be affected by the characteristics of the resin that is used, the orientation and structure of the fabricated objects and also the post-curing process.

In order to study the effect of mentioned factors, several digital objects are created. They are divided into two groups according to their shape – cube and cylinder, both with seizes 10mm. X 10mm. X 10mm. (for each of the three axes x, y, z). Each group of cubes consists of: one which is turned by a dihedral angle toward the building platform, other – turned by a trihedral angle toward the building platform, and another one - turned by a wall toward the platform. The group of the cylinders is presented by: a cylinder which is turned by a base toward the building platform, other – turned horizontally and another one which is inclined by 45° toward the platform. Along with their orientation each group of cubes and cylinders has an object that is solid, hollow and hollow with vent. The designed objects were printed from Castable Resin® and Castable Wax®, by selective laser polymerization technology by 3D printer Form 2® (Formlabs™). In addition, the layer thickness is set at 25 μm and an appropriate count of the supporting structures is chosen. **Fig. 3. Fig. 4.**

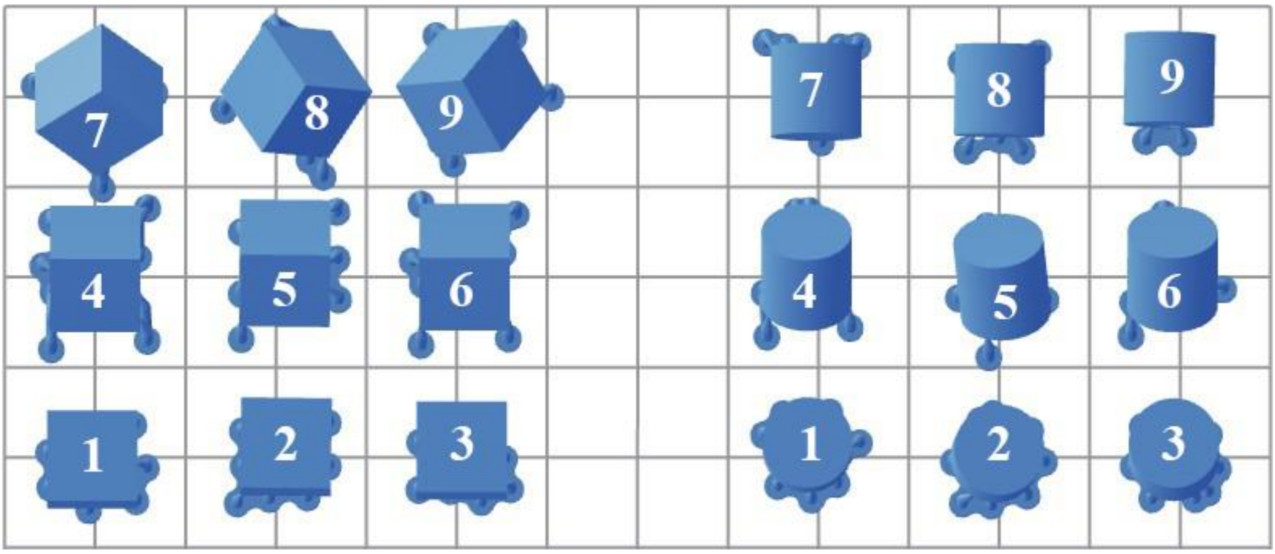


Fig.3. *An illustration of the explored objects directly from the PreForm® interface.*

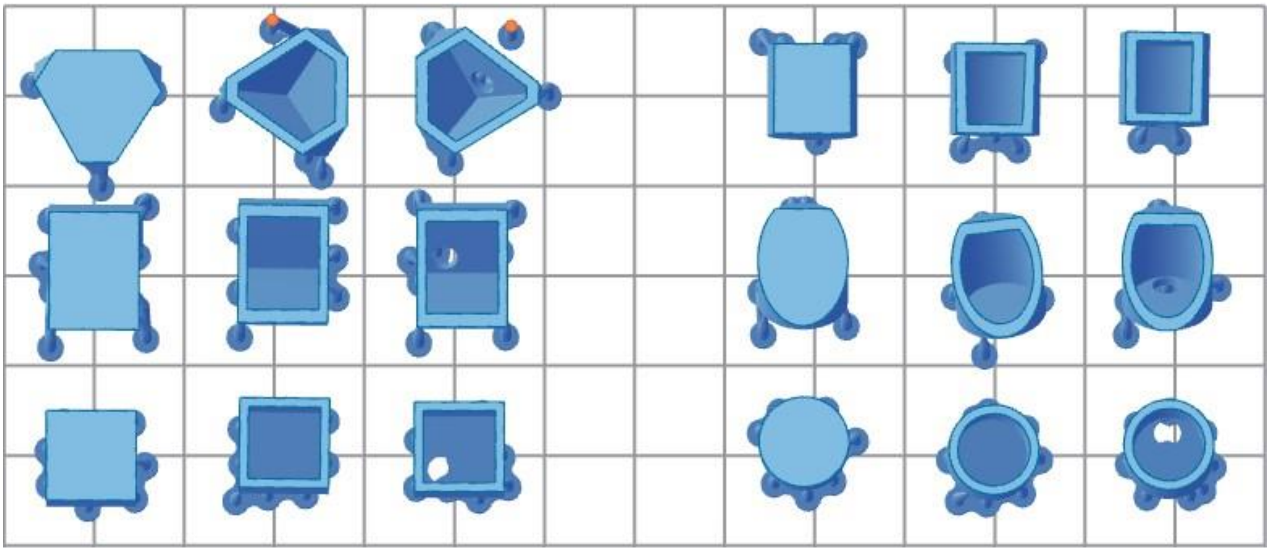


Fig.4. *A cross-sectional view of a set of 3D printed objects.*

The examined objects are measured at ten different points for each axis (x, y, z), by a digital micrometer caliper, which can read to 1μm. ($1x10^{-6}$ m.).

For the purpose of the study of **task 2.1** the mean differences between the measured sizes of each group of cubes and cylinders (according to their orientation) and the corresponding sizes of the virtual prototypes are calculated. Then the collected values of the mean difference are compared to each other.

For the purpose of the study of **task 2.2** the mean differences between the measured seizes of each group of cubes and cylinders (according to their structure) and the corresponding sizes of the virtual prototypes are calculated. Then the collected values of the mean difference are compared to each other.

For the purpose of the study of **task 2.3** the 3D printed object of Castable Resin® are post-cured as it prescribed by the producer of the resin. Then a new measurement is done, which is identical to the first one. Then the mean differences between measured sizes of each group of cubes and cylinder (according to their structure) before the post-curing and those after the post-processing are calculated. A statistical analysis of the collected results is done.

Materials and Methods Used for the Purpose of the Study of Task 3.

The burnout process of the resins is different from the one of waxes, because of the direct sublimations that is presented. The sublimation is the transition of a substance directly from the solid to the gas state, without passing through the liquid state. Thus, the wight of the pattern and temperature rate during the mold preparation for casting are essential for good casting quality.

Despite the thermal expansion that is typical for the invested relatively large objects made of resin, they may also cause a massive gas pressure to the mold walls and as a result may crack it. As a solution of this issue, a new generation of stereolithography resins that contain wax are made. Despite of this innovation a considerable part of the composition of the 3D printed objects is presented by resin, so the issue with mold cracking is still actual.

For the purpose of the study two sets of identical cylindrical objects were printed from Castable Resin® and Castable Wax®, by selective laser sintering technology and using 3D printer Form 2® (Formlabs™). The 3D printed objects of each resin are also fabricated in two sizes. In addition, the objects of each size and resin can be classified into three groups according to their structure: solid objects, hollow objects and hollow objects with vents. **Fig.5**

Fig.5. *The figure illustrates all the types of the explored objects. The specimens made of Castable Wax® are fabricated as: solid, hollow, hollow object with vents and two types depends on their size: type one – diameter – 20mm. and height – 20mm., type two – diameter – 10mm. and height 20mm. Identical specimens of Castable Resin® are made.*

For the purpose of the study custom-made casting rings of set up wax - Cavex Set Up Wax (Cavex™), are fabricated. Their size is set to provide distance between the specimen and the ring of at least 5mm.

Just before investing the specimens are aligned to the casting ring at the appropriate position. Then the type of the invested object is marked over the outer surface of the casting ring, in order to be visible after the investing procedure. **Fig.6**

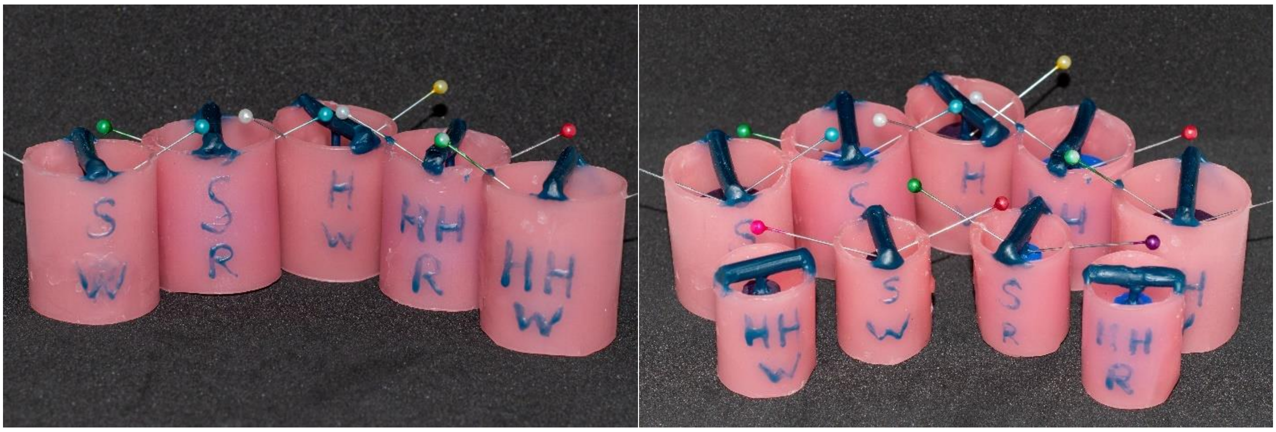
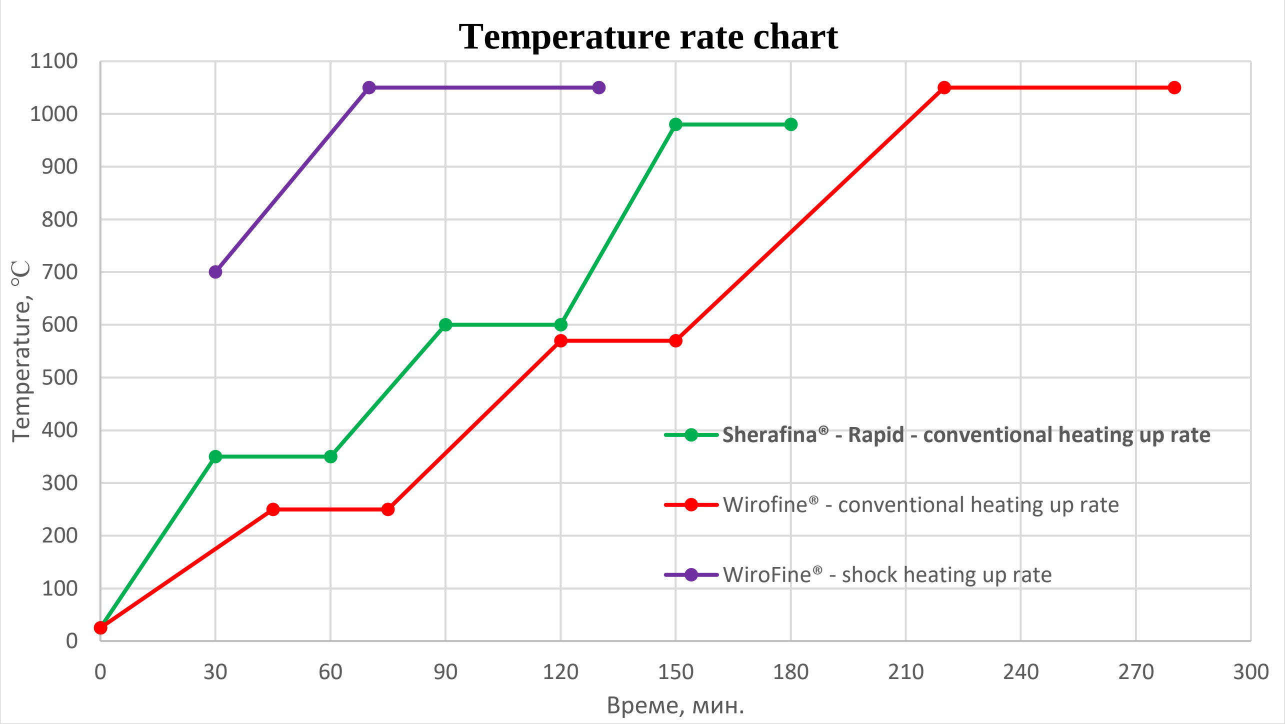


Fig.6. *The figure illustrates the custom-made casting ring and aligned specimens inside. The type of the invested object is marked over the outer surface of the casting ring as follows: SW – solid object of Castable Wax®, HW – hollow object of Castable Wax®, HHW – hollow object with vent, made of Castable Wax®, SR – solid object of Castable Resin®, HHR – hollow object with vent, made of Castable Resin®.*

The objects are invested by using two types of investment materials: WiroFine® (BEGO™), which is certificated from the manufacturer of the resins and Sherafina® - Rapid (SHERA®). After that the molds are inserted into a furnace Miditherm® 100 MP (BEGO™), they are heated by using the specific temperature rate for the examined investment materials. **Fig.7**



Фиг.7. *The temperature rates used for heating of the experimental molds.*

The following approaches are observed:

- **Evaluation of the effect of different structural configurations of printed objects to their investment molds, made of Sherafina® Rapid, during the mold preparation for casting, while a conventional heating rate is used Fig.8.**

Fig.8. *The observed molds, inserted into the furnace at 25℃.*

- **Evaluation of the effect of different structural configurations of printed objects to their investment molds made of WiroFine®, during the mold preparation for casting, while a conventional heating rate is used. Fig.9.**

Fig.9. *The observed molds made of WiroFine® and inserted into the furnace at 25℃.*

- **Evaluation of the effect of different structural configurations of printed objects to their investment molds made of WiroFine®, during the mold preparation for casting, while a shock heating rate is used. Fig.10.**

Фиг.10. *The observed molds made of WiroFine® and inserted into the furnace at 700℃.*

Every experimental approach is examined ten times as the mentioned conditions are granted and the presence of fractures over the mold surface is observed. Then the collected results are illustrated by chart and photos.

Materials and Methods Used for the Purpose of the Study of Task 4.

The proper orientation of the denture prototypes into the casting mold is a crucial condition for a good result achieved from casting process. According to the conventional methods a wax is used for fabrication and fixation of different components of the sprue system. Unfortunately, the waxes have the ability to flow under any mechanical interaction, even if they are in solid state and at room temperature. In order to reduce the negative effect of the different materials that are used and to improve the casting conditions, a method for digital arrangement of different components of the sprue system to a prefabricated mold with known dimensions.

For the purpose of the study of **task 4.1** STL-files, containing digital full-contour crown patterns of different types of teeth (in morphological aspect) are used. All of the six crowns (2 central maxillary incisors, 2 first maxillary premolars and 2 first maxillary molars) are imported into and modified by non-medical software for 3D-editioning - Autodesk Meshmixer® (Autodesk, Inc.). It allows 3D designing of different configurations of casting sprue system, as well as, the opportunity to arrange every single detail accurately at desired place to the walls of the casting ring and central thermal zone of the mold.

First of all, crown patterns are prepared for vacuum-pressure casting. By using the “Meshmix” tool six direct sprues are generated. They are designed to be straight and 2,5 mm. in diameter, as their length is set to be enough, in order to allow the distance between the most lateral points of the crowns and the prefabricated ring to be between 5 mm. and 8 mm. Then ball-shaped reservoirs are digitally made along the sprues by the “Meshmix” tool and are situated in a position to be within the thermal zone of the mold. They are set to be 5mm. in diameter. **Fig.11.**

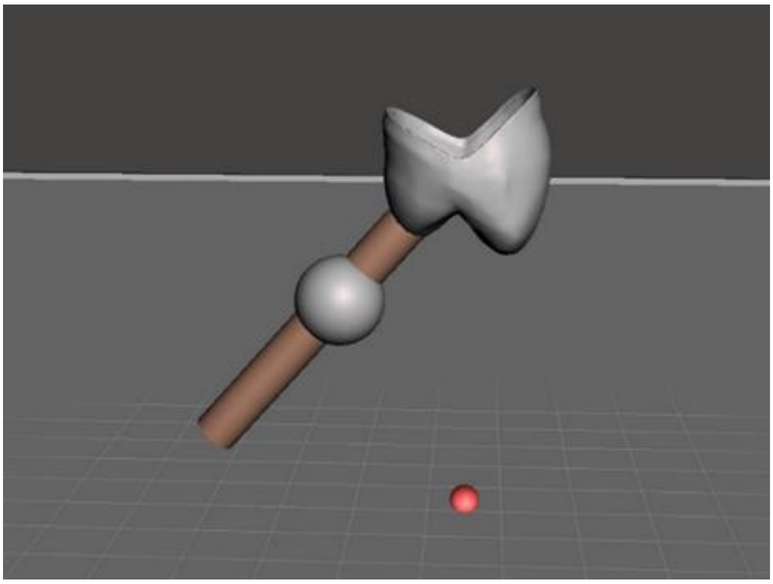
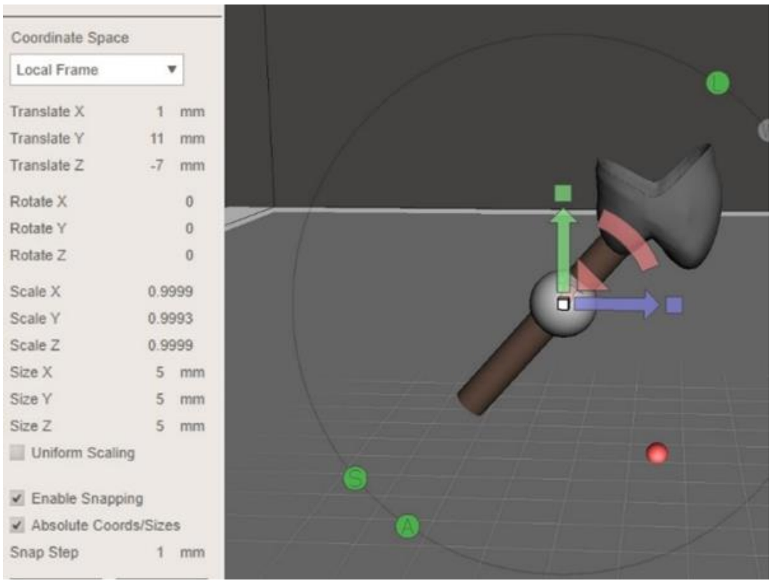


Fig.11. *The digital projection of the sprue connected to the crown pattern and also a ball-shaped reservoir arranged.*

Once the desired object is generated the software activates the “Transform tool” that allows assignment of precise measurements of the different elements as it shown on the **figure 12.**



Coordinate Space

Local Frame ▼

Translate X	1	mm
Translate Y	11	mm
Translate Z	-7	mm
Rotate X	0	
Rotate Y	0	
Rotate Z	0	
Scale X	0.9999	
Scale Y	0.9993	
Scale Z	0.9999	
Size X	5	mm
Size Y	5	mm
Size Z	5	mm

☐ Uniform Scaling

☑ Enable Snapping

☑ Absolute Coords/Sizes

Snap Step 1 mm

Fig.12*. The size can be assigned at the three axes (x, y, z). The figure shows that the measurements of the ball-shaped reservoir are 5 mm. in diameter at x axis, 5 mm. in diameter at y axis, and 5 mm at z axis.*

Then crown and the reservoir alignment check to the known size of the prefabricated casting ring can be performed. So, when the created sprue system is already connected to the casting cone, a grid integrated in the software or a special measuring tool that allows precise measurement of the desired dimensions can be used for alignment check. **Fig.13.**

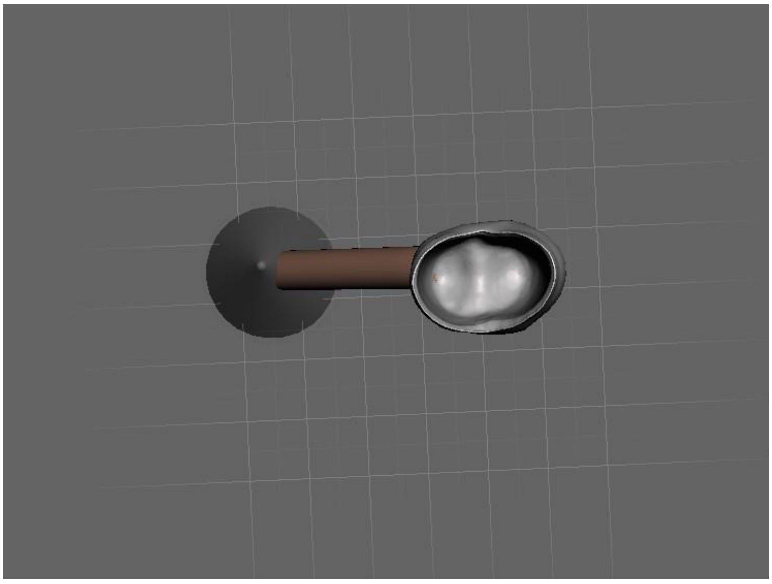


***Fig.13**. The crown is aligned to the known sizes of casting ring walls. The available grid allows good accuracy in the crown placement.*

If a better precision is needed, the software's "Measure tool" should be used. **Fig.14.**

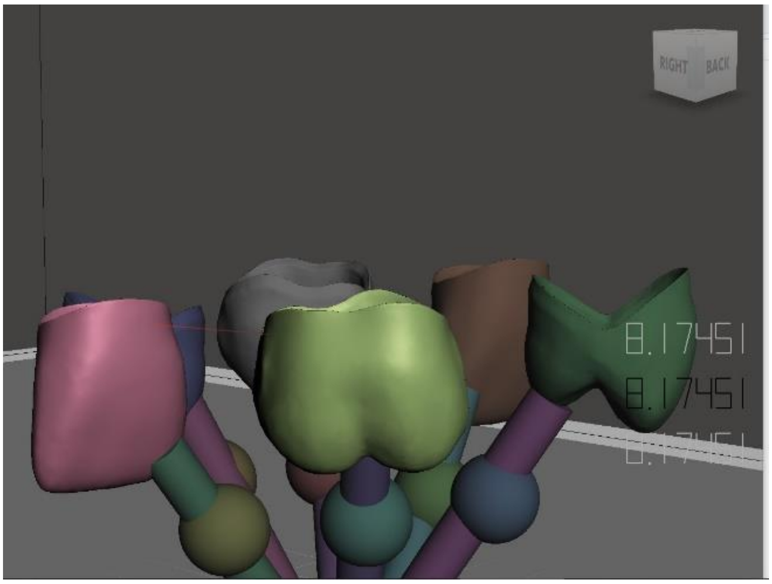


***Fig.5.** The tool called "Measure tool" allows precise check of the distance between the different generated objects with great accuracy - up to 1x10^{-5} mm.*

As a result, the casting system is designed to be in the best desired position in accordance to the dimensions of the pre-fabricated casting ring (Rapid-Ringless-System®, BEGO™).

Once the proper alignment of the first pattern of a crown is achieved, it is followed by the same procedure done for the second and all of the rest crown patterns, while a precise check of the position may be performed at any step if needed. All of casting system details are generated and situated using the same method as described and the final result is shown on **figure 15**.

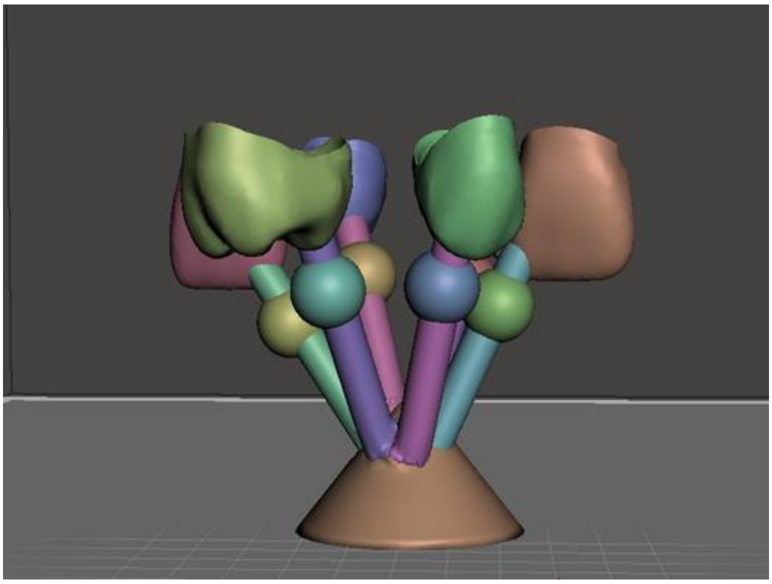


Fig.15. *The figure illustrates a digitally designed casting system, which contains casting cone, sprues, ball-shaped reservoirs and described crown patterns.*

Once the digital designing is done, a STL-file is generated and it is imported in the PreForm® software, where it is prepared for 3D-printing. The patterns are materialized by SLP technology, using 3D printer Form 2® (Formlabs™), and the certificated resin for casting – Castable Wax® (Formlabs™).

Usually in daily dental laboratory practice different in number and volume dentures have to be cast. This is the reason for the development of new approach for digital casting ring designing, which has custom and optimal dimensions.

For the purpose of the study of **task 4.2** STL-files, containing digital full-contour crown patterns of different types of teeth (in morphological aspect) are used. All of the six crowns (2 central maxillary incisors, 2 first maxillary premolars and 2 first maxillary molars) are imported into and modified by non-medical software for 3D-editioning - Autodesk Meshmixer® (Autodesk, Inc.). It allows 3D designing of different configurations of casting sprue system, as well as, the opportunity to arrange every single detail accurately at desired place to the walls of the casting ring and central thermal zone of the mold. As it mentioned according to this study a custom-made digital casting ring will be designed, so the leading factors for arrangement of the patterns will be their count and volume as well as the characteristics of the casting machine.

After the STL-files are imported in Autodesk Meshmixer®, they are prepared for casting by vacuum pressure-casting machine - Nautilus T®, BEGO™. The patterns are arranged with space between each other from 5mm. to 8mm. The same space is provided between each pattern and the smallest possible size of the casting ring. The "Measure tool" is a useful tool for setting of different dimensions. **Fig.16.**

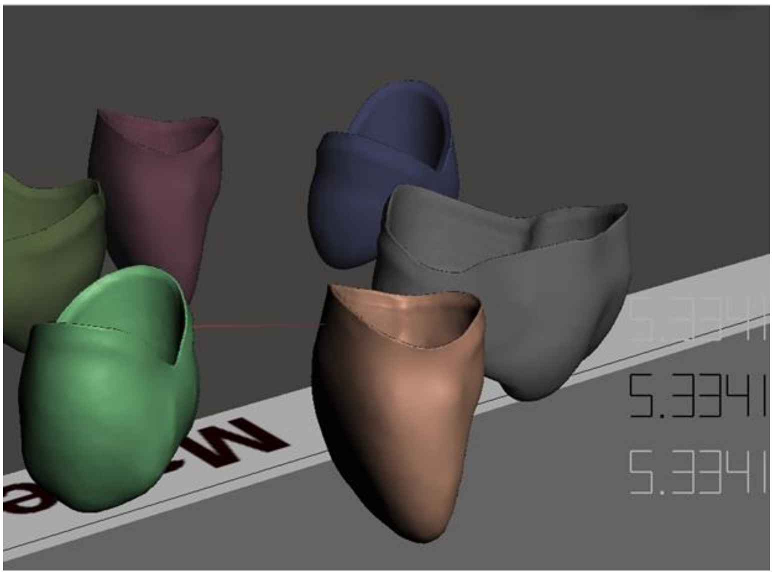
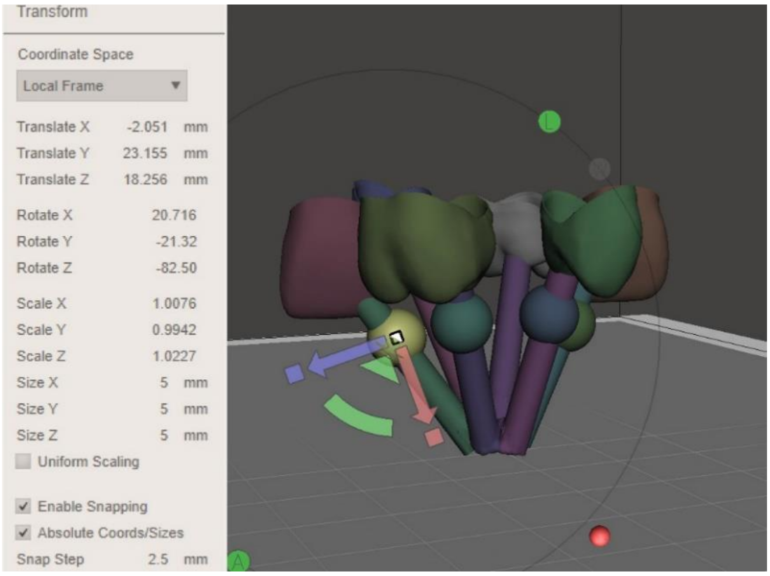


Fig.16. *The set distance between each crown is around 5,33 mm.*

The next step is creating of the sprue system. The sprues are set to be 2,5mm. in diameter and their length is set to be enough to connect the corresponding pattern to the digital projection of the casting cone. For this purpose, the "Transform tool" is used. The vector of every sprue is set at the same direction as the biggest diameter of every pattern. Then ball-shaped reservoirs are created. They are set to be 5mm. in diameter and are arranged around the central thermal zone of the mold. **Fig.17.**



Coordinate Space: Local Frame
Translate X -2.051 mm
Translate Y 23.155 mm
Translate Z 18.256 mm
Rotate X 20.716
Rotate Y -21.32
Rotate Z -82.50
Scale X 1.0076
Scale Y 0.9942
Scale Z 1.0227
Size X 5 mm
Size Y 5 mm
Size Z 5 mm
☐ Uniform Scaling
☑ Enable Snapping
☑ Absolute Coords/Sizes
Snap Step 2.5 mm

Fig.17. *Ball-shaped reservoirs are created. The „Transform tool" allows setting the desired diameter and position of each reservoir.*

After the sprue system is done, then a casting cone is created and the following adjustment of the sprues in accordance to the cone configuration is done. Finally, a casting ring is created in accordance to the configuration of the sprue system. As it mentioned the casting ring is generated 5mm. to 8mm. away from the crown patterns. **Fig.18.**

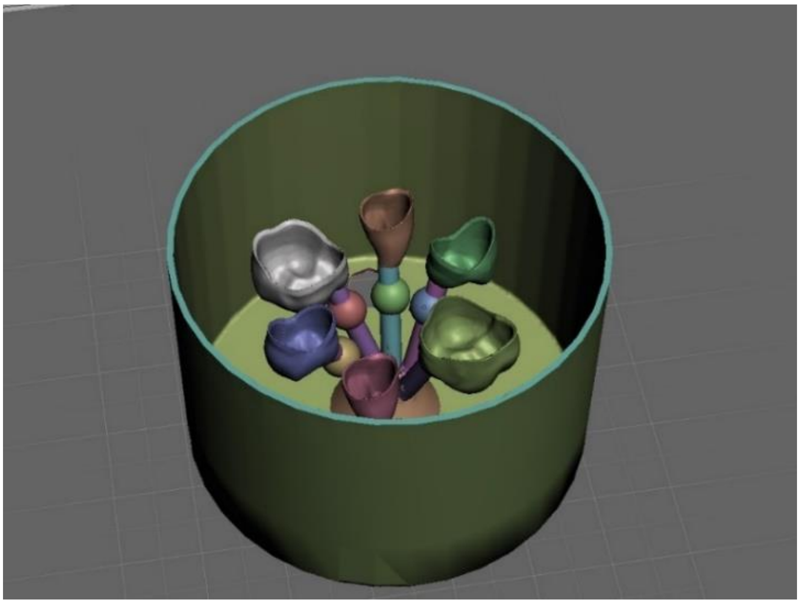


Fig.18. *The final result of the presented approach. The sprue system, the casting cone and the casting ring are designed as a single object, which is 3D printed afterwards.*

The patterns are materialized by SLP technology, using 3D printer Form 2® (Formlabs™), and the certificated resin for casting – Castable Wax® (Formlabs™).

CHAPTER THREE

COMPARATIVE STUDY OF THE TEMPERATURE RELATED PHYSICAL CHANGES AND THE PRESENCE OF RESIDUAL ASH CONTENT OF DIFFERENT MATERIALS USED FOR FABRICATION OF PATTERNS (BY MILLING, CAD/CAM AND SLP) FOR CASTING FROM DENTAL ALLOYS

The temperature related changes of the materials are recorded by camera and are presented by photos. The residual ash remnants are collected after the burnout procedure and are observed by an analytic balance.

1. Comparative study of the temperature related physical changes of different materials for fabrication of patterns (by milling, CAD/CAM and SLP) for casting from dental alloys.

After insertion in the furnace and when the temperature reaches 100°C, there aren't any significant visual changes registered. **Fig.19.**

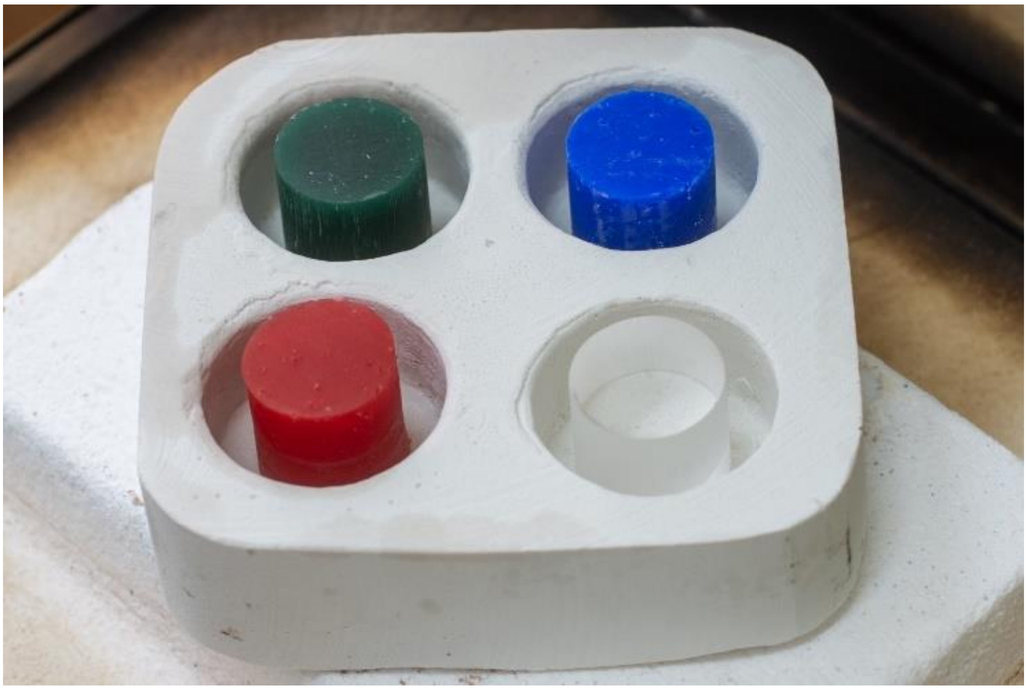


Fig.19. *The four samples at temperature of 100°C.*

At temperature of 150°C almost all of the samples don't show any significant changes, except slight changes in the CAD/CAM wax specimen. Its edges start looking round and the surface has a mat texture. **Fig.20**

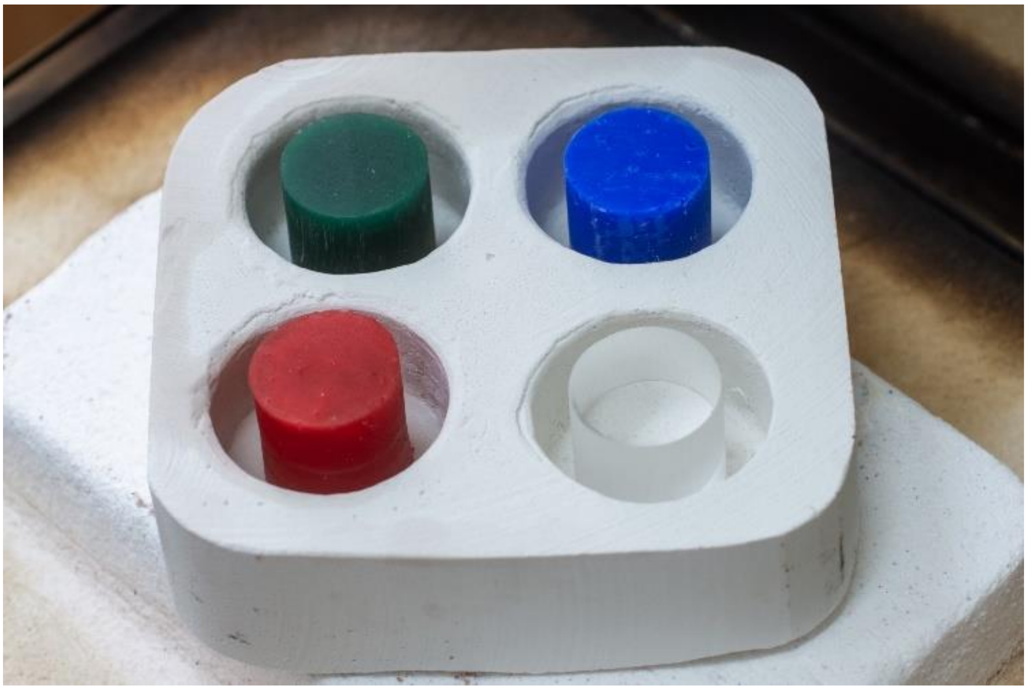


Fig.20. *No changes at 150℃ in comparison to 100℃.*

At 200℃ the CAD/CAM wax sample starts melting. The Pattern Resin LS™ (GC™) starts its temperature expansion. The upper surface of the sample made of Pattern resin LS™ starts bending and expanding. It is apparent that the diameter of the upper base of the cylindrical specimen is bigger than the lower one, which is result of the temperature difference between the pot and the air inside the furnace. When the C-cast® resin and Castable Resin® are inspected, there aren't any visible changes available. **Fig.21-A**

After the 10 minutes hold, the CAD/CAM wax sample is already melted and starts boiling. The Pattern Resin LS® continues its expansion. According to the pattern made of C-cast® and Castable Resin®, no any changes are visible. **Fig.21-B**

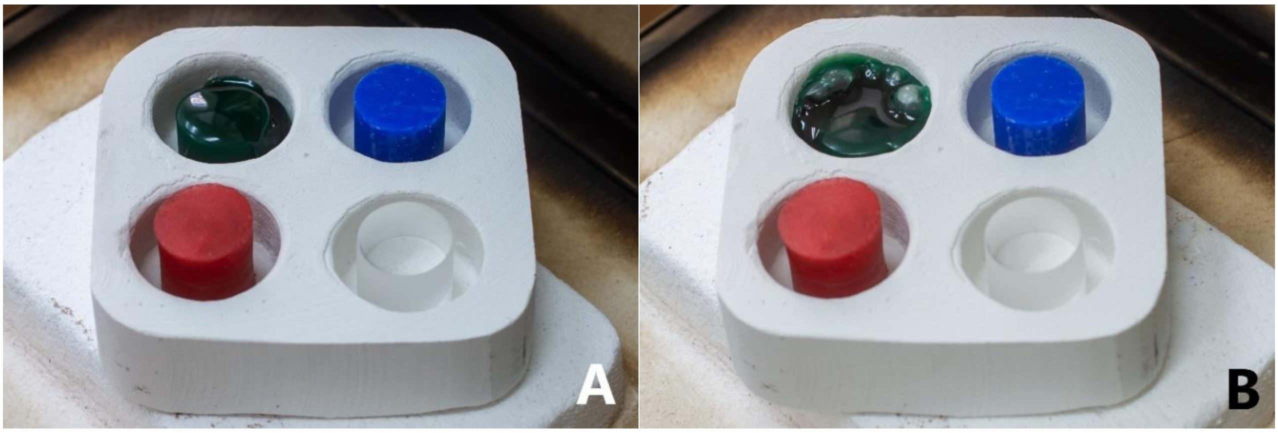


Fig.21. *Structural changes of the samples at 200℃, before (A) and after (B) the 10 minutes hold.*

At the temperature of 250℃ the wax pattern is still boiling. The expansion of the sample made of Pattern Resin LS™ become significant and more evident. When inspecting the Castable Resin® sample the first visible signs of expansion are visible. A tiny fissure is presented over the base of the Castable Resin® cylinder, which is clear evidence for thermal expansion of the detail. It is apparent that fissures are parallel to the direction of the different layers. As of the possible reason for this phenomenon may be the lower energetic content of this space between the layers, due to presence of many free ends of the polymer chains between the printed layers. There aren't any visible changes to C-cast® pattern, in contrast to the rest of the specimens. **Fig.22 – A.**

At the end of the 10 minutes hold Pattern resin LS™ sample start bending around its altitude, while its base looks bulkier and more rounded. At this level some other changes in Castable Resin® pattern become visible, it becomes a little darker in color and the count of the fissure is increased. The C-cast® shows still no changes. **Fig.22 - B.**

Fig. 22 – A. *Structural changes of the samples at the moment that 250℃ is reached.*

***Fig.22 - B.** Structural changes of the samples at 250oC, after the 10 min. hold.*

There aren’t any significant changes between 250℃ and 300℃, so a picture of the samples at the temperature of 300℃ after the hold is presented. It is apparent that a little amount of the CAD/CAM wax sample is evaporated. The Pattern resin LS™ sample almost twice its volume and become porous because of the excessive expansion. Due to coloring agent burn-out, Castable Resin® sample becomes more and more darker and it still hasn’t any significant volumetric changes. It is interesting to note that even at this temperature level there aren’t any visible physical changes in C-cast® pattern. **Fig.23.**

***Fig.23.** Structural changes of the samples at 300℃, after the 10 minutes hold.*

At 350°C the described Castable Resin® specimen signs of expansion become more and more evident. The C-cast pattern becomes porous, without any visible volumetric changes. The thermal expansion of the C-cast specimen can be noticed after the hold at 350°C. A superficially melting of the Pattern Resin LS™ is visible. At the same time an initial carbonization of single components the CAD/CAM wax sample is visible like a black peel. **Fig.24.**

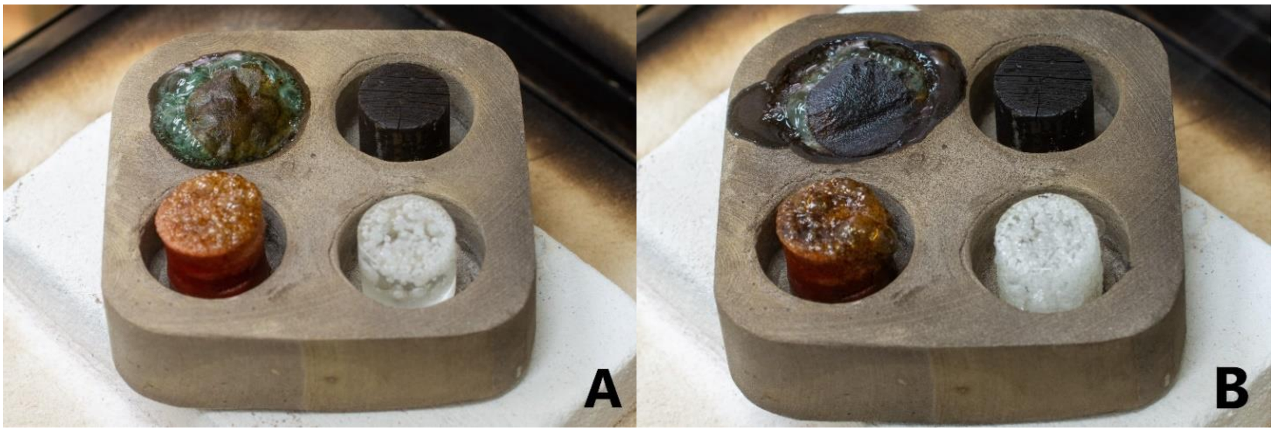


Fig.24. *Structural changes of the observed samples at 350°C, before (A) and after (B) the 10 minutes hold.*

The described changes at 350°C are also manifested at 400°C, but more clearly. The CAD/CAM wax specimen continues its carbonization. The Pattern Resin LS™ is melted and it starts boiling as well as some components of the resin are carbonized (the black zones of the Pattern Resin LS™ sample's nest). C-cast® pattern has a reduced volume, it starts to lose its structure. The expansion of the Castable Resin® pattern is apparent, and its surface become shiny, because of the melting of the auxiliary components of the resin. **Fig. 25.**

Fig.25. *Structural changes of the observed samples at 400°C.*

Between 450℃ and 550℃ the rapid burning process is apparent. As a result, the C-cast® and Pattern resin LS™ samples show almost lack of residual ash remnants. In contrast to them the CAD/CAM wax and Castable Resin® samples leaves some amount of residuum, which will be reduced significantly during further temperature rise. **Fig.26.**

Fig.26. *Structural changes of the samples at 550℃.*

At 600℃ the remnants of CAD/CAM wax and Castable Resin® dramatically reduce their volume. **Fig.27.**

Fig.27. *Structural changes of the observed samples at 600℃.*

Between 600°C and 1050°C there aren't any major changes, except the reduction of the ash remnants that are left by the wax and Castable Resin® samples. Therefore, the final result at 1050°C is illustrated at **fig.28.**

Fig.28. *Residual ash amount reduction at 1050°C.*

After the burnout process, the sample of Castable Resin® and CAD/CAM left a little amount of ash content.

2. Comparative study of the presence and the amount of the residual ash remnants after the examined patterns burnout.

After 1050°C is reached and the refractory pot is removed from furnace to cool down, an examination of the residual ash content is done. **Fig.29.**

Фиг.29. *Residual ash content left after burn-out of the four examined specimens.*

It is apparent that the wight of the ash content that is got from the specimen of CAD/CAM wax is absolutely insignificant. Nevertheless, a check is made by analytic balance. The weight of the ash content is less than 0,001g. Having in mind that the weight of the initial specimen is around 5,5g., a conclusion can be made that its ash content after bur-out is less than 0,02%, which determines it as insignificant.

When the weight of ash content of Castable Resin® is checked, a similar result is achieved. Its weight is less than 0,001g. Having in mind that the weight of the initial specimen is around 7g., a conclusion can be made that its ash content after bur-out is less than 0,02%, which determines it also as insignificant.

3. Discussion.

The physical changes of the observed materials in the course of the thermal elimination of the pattern are strictly related to their chemical structure.

If we observe the CAD/CAM wax sample, it is obvious that it melts at around 200°C, without any major visible expansion of the solid state, which prevents the mold form crack. It has the properties to be very good material for pattern fabrication, which is also easy to work with. Despite all of these advantages, it has one major disadvantage, as a wax it has the ability to flow under prolonged mechanical interaction or due to temperature rising. This is a factor that may cause any kind of deformations of the patterns. Thus, the fabricated patterns should be kept away from any additional mechanical interactions or temperature changes and should be invested as fast as possible as a prevention of any deformation of patterns.

When Pattern Resin LS® sample is observed an excessive thermal expansion during burnout process is obvious. This may cause a mold fractures, as a result of the rising pressure against the mold walls and also the high melting temperature. As a prevention of that the producer recommends a wax coverage of the outer pattern walls to be made and investment material with higher strength to be used. Otherwise, it is firm and stiff material which allow fabrication of a pattern with great abilities to withstand to mechanical and thermal interactions and also acceptable accuracy.

If the C-cast® is examined it is apparent that it has physical properties which are almost identical to the Pattern resin LS®. The main component of both materials is methyl methacrylate, both of them are firm and stiff materials and don't leave any residuals after burning out. The C-cast® material has a little thermal expansion and changes in its structure are visible at a higher temperature. These characteristics makes the material suitable for fabrication of patterns which are not susceptible to any physical interactions and are firm and stable. Unfortunately, there isn’t much information about the physical properties of this material at the scientific literature.

The Castable Resin® is a resin-based material that is produced by Formlabs™ for their 3D-printers. When the material is heated it starts to sublimate and keeps its solid state for a long period, as a result a massive thermal expansion is available. This may cause mold fractures, due to thermal expansion of the solid structure on one hand, and on the other hand as a result of massive gas pressure against mold walls. Otherwise, the material is stiff and firm against any mechanical interactions and also allows fabrication of patters with great accuracy and dimensional stability.

Pattern resin LS® and C-cast® leaves no ash remnants after burn-out in contrast to Castable Resin® and CAD/CAM wax, which generate a little and insignificant quantity of ash content. A conclusion can be made that the remnants that are left from all four examined materials are too less and won’t affect the result of further casting procedure significantly.

All of the observed materials have advantages and also disadvantages. In order to gain a cast with good qualities some modifications of the production process need to be made, according to specific physical properties of the materials.

4. Conclusions:

- Although the CAD/CAM wax is based on wax, it leaves a little and insignificant amount of residual ash remnants. As wax it has low melting temperature which is close to the room temperature.

- Pattern Resin LS® leaves no any ash content after burnout, but is has an extremely heigh coefficient of thermal expansion and heigh melting temperature. In order to gain a cast with good properties, some modifications of the production process have to be made according to specific physical properties of the material.

- C-cast® doesn’t leave any ash remnant after burnout. The material shows less thermal expansion than the specimen of Pattern Resin LS®, but also has a heigh melting temperature. In order to gain a cast with good qualities, some modifications of the production process have to be made according to specific physical properties of the materials.

- C-cast® and Pattern Resin LS® have almost the same chemical structure, but their temperature related physical properties are too different.

- Castable Resin® leaves a little and insignificant amount of ash residuals after burnout, it is has moderate to heigh coefficient of thermal expansion. During the experiment only melting of single components of the material is registered, but not complete liquefy. Considering these facts and in order to gain a cast with good properties, some modifications of the production process have to be made according to specific physical properties of the material.

- The temperature related physical characteristics and the amount of the ash content that leaves Castable Resin®, specify it as suitable for use in dental medicine.

- Considering the variety of materials for pattern fabrication and their specific physical properties and in order to receive a quality cast, some modifications of the production process have to be made.

- Despite the presence of some ash content after burnout, its amount is very little and provide an opportunity for gaining a cast with good properties.

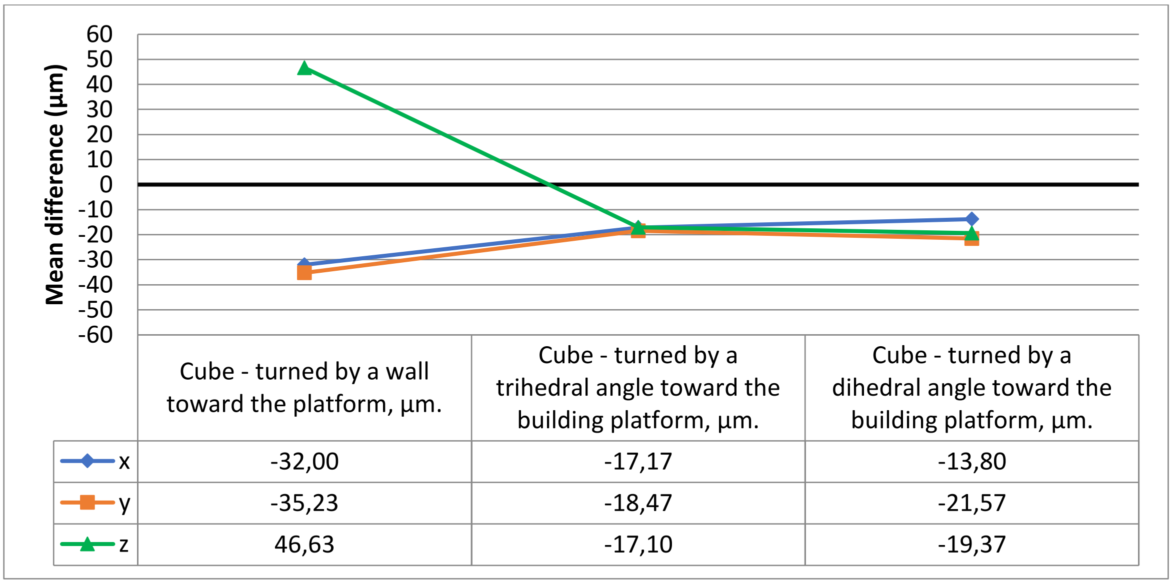
CHAPTER FOUR

EVALUATION OF THE PRODUCTION ACCURACY OF OBJECTS MADE BY SLP 3D PRINTING TECHNOLOGY

The collected results are imported in a computer database, which is used for preparation of statistical analysis. Then the results of the analysis are interpreted and exported as charts.

1. Comparative study of the 3D printing accuracy of objects with different orientation during the production process, while two types castable resins are observed.

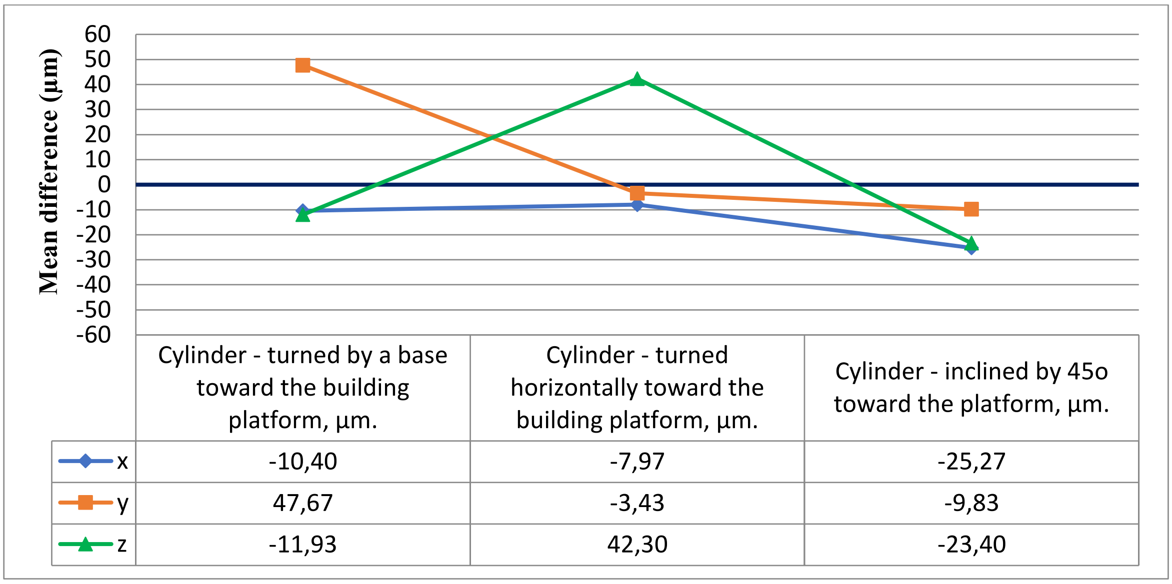
After the measurements are done, the collected data is used for calculation of the mean difference between the measured sizes of the examined objects and the digitally set sizes for the virtual patterns. The observed mean difference is the least for cubes, which are positioned by a trihedral angle toward the building platform. When the cubes turned by dihedral angle toward the platform are examined, almost the similar result is achieved. The objects of both groups are with smaller size than the set. The highest deviation is observed to the group of cubes that are oriented by a facet to the building platform. It is remarkable that along the **z** axis the objects are bigger compared to the values are set, while along the **x** and **y** axes they are smaller. **Fig.30.**



	Cube - turned by a wall toward the platform, µm.	Cube - turned by a trihedral angle toward the building platform, µm.	Cube - turned by a dihedral angle toward the building platform, µm.
◆ x	-32,00	-17,17	-13,80
■ y	-35,23	-18,47	-21,57
▲ z	46,63	-17,10	-19,37

Fig.30. *The calculated mean difference values of cubes made of Castable Resin®, grouped by their orientation.*

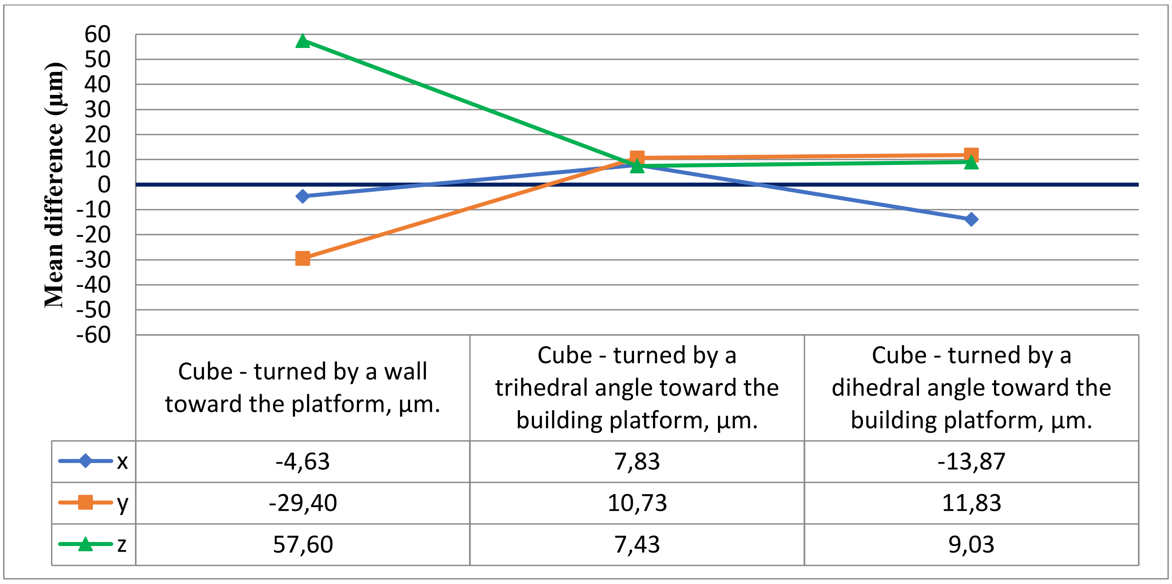
When the cylinders of Castable Resin® are examined, the lowest value of the mean difference is observed to those which are inclined by 45 ° toward the building platform. They are also smaller than their virtual prototypes. The rest of the cylinders are bigger than their digital prototype only in the direction parallel to the building vector. Otherwise, the measurements in the other directions show lower values than those are set. **Fig. 31.**



	Cylinder - turned by a base toward the building platform, μm.	Cylinder - turned horizontally toward the building platform, μm.	Cylinder - inclined by 45o toward the platform, μm.
◆ x	-10,40	-7,97	-25,27
■ y	47,67	-3,43	-9,83
▲ z	-11,93	42,30	-23,40

***Fig.31.** The calculated mean difference values of cylinders made of Castable Resin®, grouped by their orientation.*

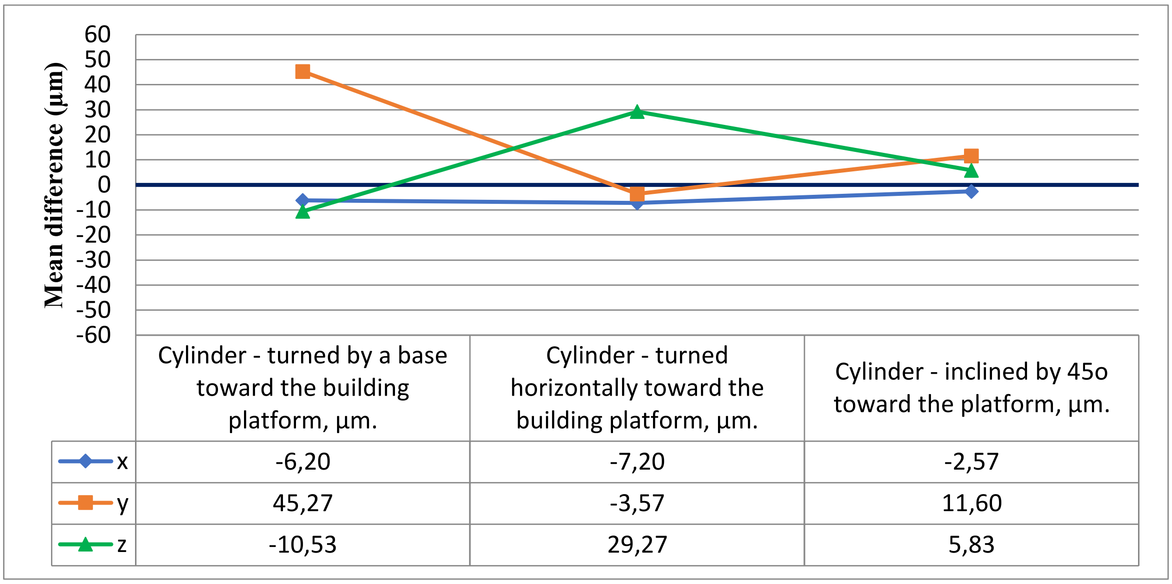
When the collected results for cubes of Castable Wax® are examined, the cubes with two parallel walls to the building platform shows higher deviation to the set sizes. Furthermore, the main deformations are presented in direction parallel to the building vector again. The tendency of less deviation, typical for cubes with dihedral and trihedral angle, to the building platform is confirmed also in these groups. **Fig.32.**



	Cube - turned by a wall toward the platform, μm.	Cube - turned by a trihedral angle toward the building platform, μm.	Cube - turned by a dihedral angle toward the building platform, μm.
◆ x	-4,63	7,83	-13,87
■ y	-29,40	10,73	11,83
▲ z	57,60	7,43	9,03

***Fig.32.** The calculated mean difference values of cubes made of Castable Wax®, grouped by their orientation.*

The results for cylinders of Castable Wax® are identical to those for the other explored resin. The main difference between two identical group of specimens, which are made of two different resins, is that the object of Castable Wax® shows less deviation than those made of another resin. **Fig.33.**



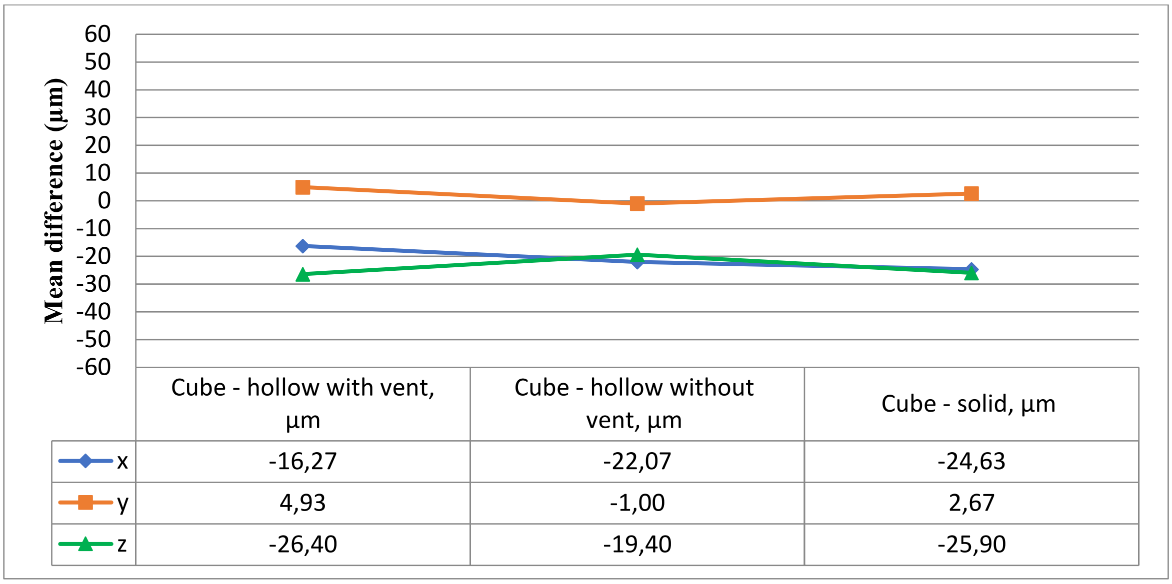
	Cylinder - turned by a base toward the building platform, µm.	Cylinder - turned horizontally toward the building platform, µm.	Cylinder - inclined by 45o toward the platform, µm.
x	-6,20	-7,20	-2,57
y	45,27	-3,57	11,60
z	-10,53	29,27	5,83

Fig.33.*The calculated mean difference values of cylinders made of Castable Wax®, grouped by their orientation.*

2. Comparative study of the 3D printing accuracy, when objects with different structure are fabricated of Castable Resin® and Castable Wax®.

The structure of the printed objects should also affect the printing accuracy. It can be digitally modified and as a result allows creation of objects with identical form and sizes but different mechanical and physical characteristics, which affects the further processing. In context of the mentioned statement, it is essential the printing accuracy to be checked as different in structure objects and made of different resins are observed.

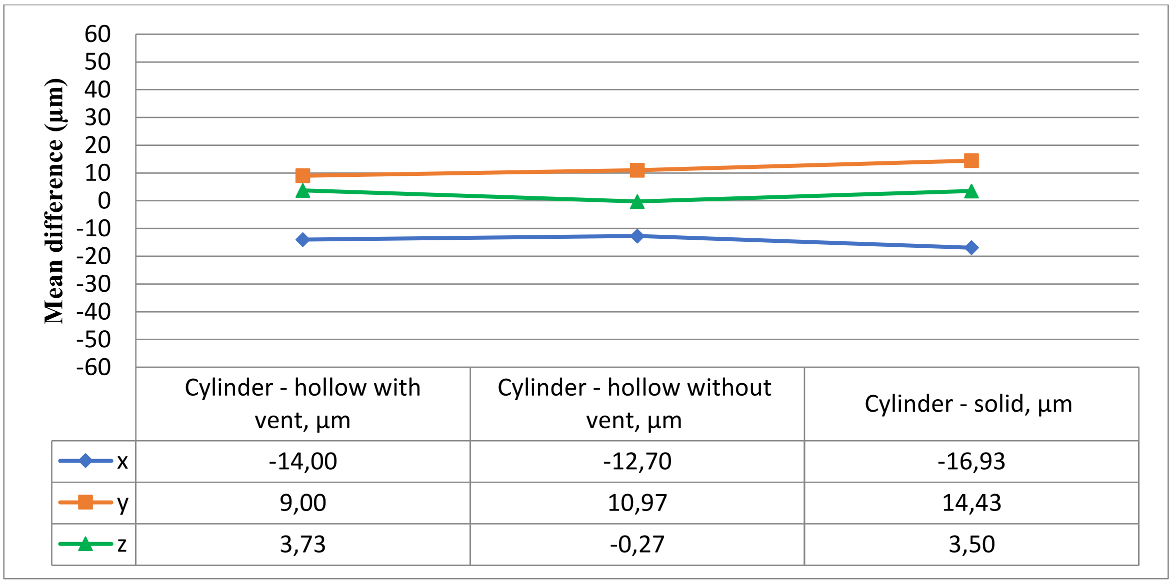
The mean differences between each group of cubes (by their structure) of Castable Resin® and those that are digitally set is calculated. Then the collected values for the mean difference of each group are compared in between for each axis. When the results of the comparison are observed, no any significant difference are found. The largest deviation between the three explored groups is around 8,36 μм. Having in mind the abilities of the contemporary 3D printers and scanners this difference can be characterized as insignificant.



	Cube - hollow with vent, µm	Cube - hollow without vent, µm	Cube - solid, µm
x	-16,27	-22,07	-24,63
y	4,93	-1,00	2,67
z	-26,40	-19,40	-25,90

Fig.34. *The calculated mean difference values of cubes made of Castable Resin®, grouped by their structure.*

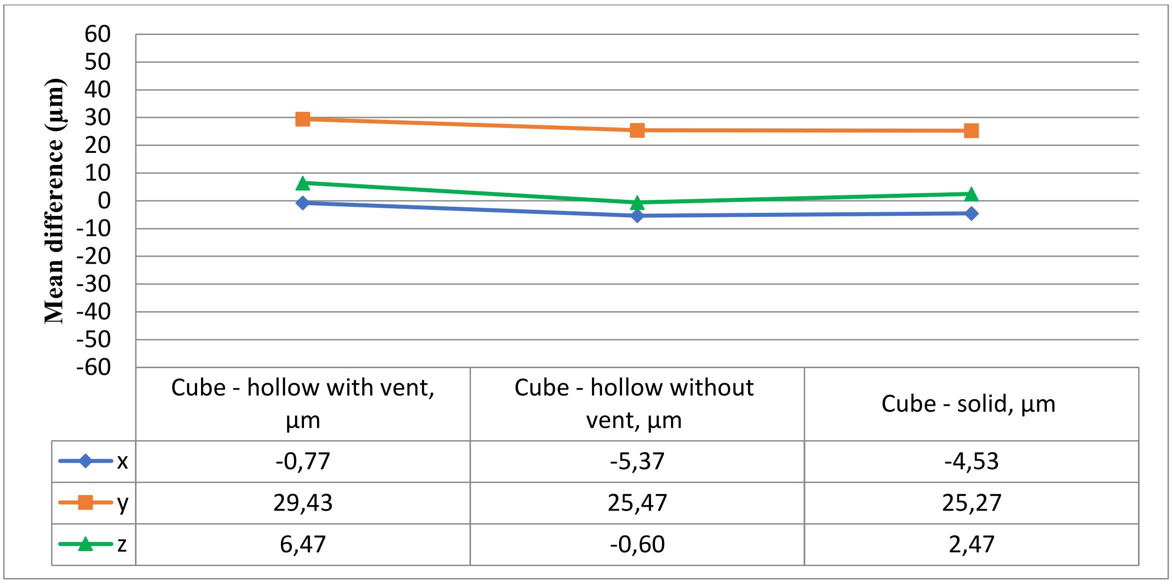
When the calculated result for the cylinders of Castable Resin® are analyzed, the same conclusion can be made as the previous examined. When the calculated values for each axis of the three observed groups are compared, it is apparent that the differences aren't higher that 6 µm. **Fig.35.**



	Cylinder - hollow with vent, µm	Cylinder - hollow without vent, µm	Cylinder - solid, µm
x	-14,00	-12,70	-16,93
y	9,00	10,97	14,43
z	3,73	-0,27	3,50

Fig.35. *The calculated mean difference values of cylinders made of Castable Resin®, grouped by their structure.*

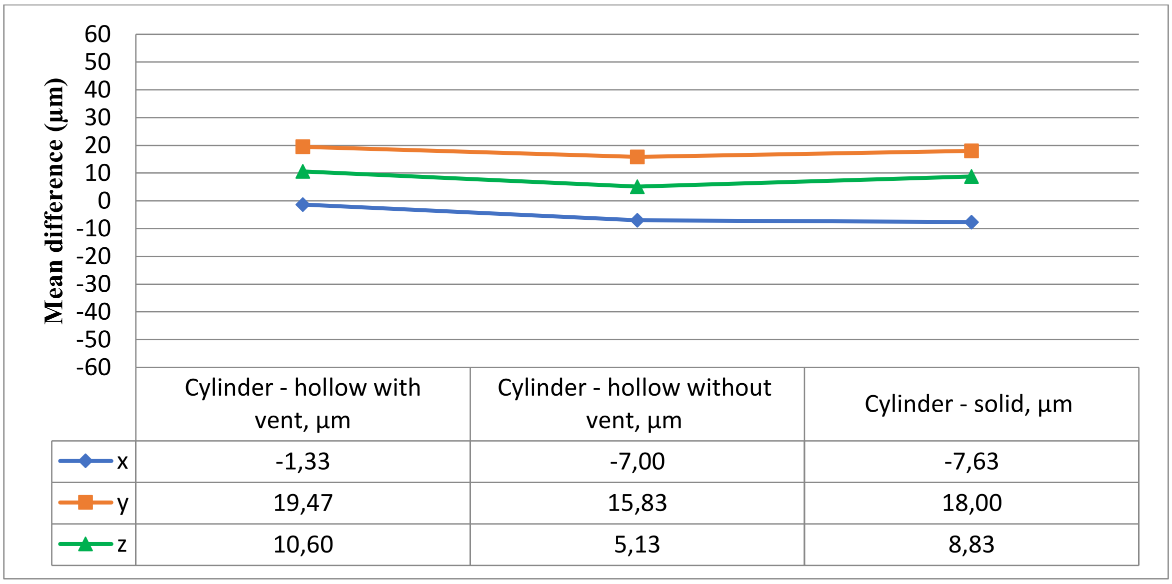
As the cubes of Castable Wax® are examined the results are almost identical. Comparing the calculated values for each axis of the three observed groups, it is apparent that the differences aren't higher than 7 µm. **Fig.36**



	Cube - hollow with vent, µm	Cube - hollow without vent, µm	Cube - solid, µm
x	-0,77	-5,37	-4,53
y	29,43	25,47	25,27
z	6,47	-0,60	2,47

Fig.36. *The calculated mean difference values of cubes made of Castable Wax®, grouped by their structure.*

The highest calculated difference between the three examined groups of cylinders (made of *Castable Wax®*) is no more than от 6,3 µm. This as previously mentioned differences are not significant as far as the 3D printing accuracy is concerned.



	Cylinder - hollow with vent, µm	Cylinder - hollow without vent, µm	Cylinder - solid, µm
x	-1,33	-7,00	-7,63
y	19,47	15,83	18,00
z	10,60	5,13	8,83

Fig.37. *The calculated mean difference values of cylinders made of Castable Wax®, grouped by their structure.*

3. Evaluation of the influence of the postcuring process to the 3D printed objects of Castable Resin®.

The results of the study are imported in a computer database and the mean values and mean differences are calculated for each group of objects. Then a statistical analysis is made. The result of calculations and analysis are presented at **table 1.**

Table 1. *Mean values ± standard error, mean difference, confidence interval of the difference, T-value and P-value for identical groups of cylinders (by their structure and made of Castable Resin®) before and after the post curing process are presented.*

	Mean values, mm. ± standard error, mm.	Mean difference, mm.	95% *confidence interval of the difference*	t	P
Cylinder – hollow with vent					
Axis: x					
Before post-curing	9,98600±0,001063	0,000933	[-0,002072;0,003939]	0.703	0.500
After post-curing	9,98507±0,000868				
Axis: y					
Before post-curing	10,00900±0,001306	0,002367*	[0,000869; 0,003864]	3,575	0,006
After post-curing	10,00663±0,001238				
Axis: z					
Before post-curing	10,00373±0,003931	0,001500	[-0,005769; 0,008769]	0,467	0,652
After post-curing	10,00223±0,001690				
Cylinder – hollow without vent					
Axis: x					
Before post-curing	9,98730±0,000568	0,000467	[-0,002305; 0,003239]	0,381	0,712
After post-curing	9,98683±0,000923				
Axis: y					
Before post-curing	10,01097±0,001589	0,001033	[-0,000666; 0,002732]	1,376	0,202
After post-curing	10,00993±0,001198				
Axis: z					
Before post-curing	9,99973±0,001345	0,000833	[-0,001261; 0,002928]	0,900	0,392
After post-curing	9,99890±0,001347				
Cylinder - solid					
Axis: x					
Before post-curing	9,98307±0,000227	0,000233	[-0,000998; 0,001465]	0,429	0,678
After post-curing	9,98283±0,000437				
Axis: y					
Before post-curing	10,01443±0,002504	0,002200	[-0,002119; 0,006519]	1,152	0,279
After post-curing	10,01223±0,001564				
Axis: z					
Before post-curing	10,00350±0,001469	0,002767*	[0,000596; 0,004938]	2,883	0,018
After post-curing	10,00073±0,001138				

The significant results according to the statistical analysis are marked with „*“.

It is essential to note that the mean difference is calculated by subtracting the mean values of a single group objects measured before post curing and those for identical group after post curing. It is calculated for each axis of the observed groups. As the table is observed, the minimal values for mean difference between identical group of objects (for each axis) is 0,000233 µm., and the maximum is 0,002767 µm. As they are presented these values may be considered as negligible. However, when the T-value and P-value are observed, the situation looks different. The T-value for some objects is higher than the critical for the data set (1,96) and respectively the P-value is higher than the significance level for the current data set. As a result, the mean differences between identical groups of objects are very little as value but these differences are statistically significant. It means that the post-curing process cause deformations to the cylindrical specimens.

Identical analysis is made for the cylinders of Castable Resin®, when they are examined before and after the post-curing process. The results are presented at **table 2.** As the table is observed, the minimal values for mean difference between identical group of objects (for each axis) is 0,001636 mm. and the maximum is – 0,043821 mm. The most of the values for the mean difference may be considered as negligible. However, when the T-value and P-value are observed, the situation looks different. The T-value for some objects is higher than the critical for the data set (1,96) and respectively the P-value is higher than the significance level for the current data set. As a result, the mean differences between identical groups of objects are very little as value but these differences are statistically significant. It means that the post-curing process cause deformations to the cubic specimens.

Table 2. *Mean values ± standard error, mean difference, confidence interval of the difference, T-value and P-value for identical groups of cubes (by their structure and made of Castable Resin*$^{®}$*) before and after the post curing process are presented.*

	Mean values, mm. ± standard error, mm.	Mean difference, mm.	95% *confidence interval of the difference*	T	P
Cube – hollow with vent					
Axis: x					
Before post-curing	9,98380±0,001093	0,002936*	[0,000099;0,004301]	2,369	0,042
After post-curing	9,98160±0,000733				
Axis: y					
Before post-curing	10,01660±0,011377	0,043821	[-0,023748;0,038948]	0,548	0,597
After post-curing	10,00900±0,005972				
Axis: z					
Before post-curing	9,97380±0,000490	0,003062	[-0,000591;0,003791]	1,652	0,133
After post-curing	9,97220±0,000712				
Cube – hollow without vent					
Axis: x					
Before post-curing	9,97790±0,000567	0,001776*	[0,001329;0,003871]	4,628	0,001
After post-curing	9,97790±0,000567				
Axis: y					
Before post-curing	9,99910±0,001683	0,002781*	[0,000211;0,004189]	2,502	0,034
After post-curing	9,99690±0,001320				
Axis: z					
Before post-curing	9,98060±0,000806	0,003164	[-0,000963;0,003563]	1,299	0,226
After post-curing	9,97930±0,000448				
Cube - solid					
Axis: x					
Before post-curing	9,97530±0,000775	0,003169	[-0,000667;0,003867]	1,596	0,145
After post-curing	9,97370±0,000775				
Axis: y					
Before post-curing	10,00270±0,000746	0,004442	[-0,001378;0,004978]	1,281	0,232
After post-curing	10,00090±0,001888				
Axis: z					
Before post-curing	9,97420±0,000327	0,001636*	[0,000529;0,002871]	3,285	0,009
After post-curing	9,97250±0,000401				

The significant results according to the statistical analysis are marked with „*“.

4. Discussion.

The objects, which base or just a wall is turned toward the building platform in the process of 3D printing, show the highest degree of distortion of all of the examined objects. It is important to note that the layer thickness is set to 25 μm. Actually, when the first layer is cured and the building platform goes down for a new layer deposition, the generated forces as a result of the hydrostatic pressure of the liquid resin drive the cured layer to bend. Further deposition of the second and each following layer is done over a deformed base provided by the configuration of the first layer. As a result, an elongation of the object’s size, which is parallel to the vector layer 3D printing process, is achieved. In order to be overcame the mentioned issue, a different object orientation is recommended. The smaller the first printed layers surface is, the better the accuracy of 3D printing process will be. That’s the reason why the cubes which angel is turned toward the building platform show less deformation. The same tendency is observed, when the cylindrical objects are examined. In this case the most appropriate orientation for the cylinders is when they are inclined by any angle close to 45^{o}. In this case the surface of the first deposed layer will be the least possible.

Another reason for the explored phenomenon is that the SLP is done by a coherent shaft of light emitted by a laser. Thus, a huge amount of energy is concentrated over the layer which is under deposition. As a result, an extra heat is generated to the curing layer, which cause its thermal expansion and respectively its deformation.

Along with the observed factors that affect the 3D printing, the type of the used resin is also important. The results show that Castable Wax® is the material that allows a better accuracy to be achieved in comparison to Castable Resin®. In fact, the cast is not considered as an accurate process for pattern replacement, so in this context both of the used resins are suitable for dental use.

The object structure doesn’t affect the 3D printing accuracy. The results show that deviation between the explored groups of objects with a specific structure is from 6 μm. to 9,43 μm. These values are absolutely insignificant, when the characteristics of the contemporary 3D printers and scanner are observed.

After evaluation of the results for the effect of post-curing process to accuracy of SLP technology, a discrepancy is shown between the measurements made to a single object before and after the post-curing process. Although, the post-curing process provides an extra resistance to tensile forces for the patterns, it leads to an object shrinkage. Even if the 3D printed objects aren’t post-cured, they have better mechanical properties than the wax. Thus, the post-curing process can be considered as unnecessary and also time consuming.

5. Conclusions:

- The objects, which base or just a wide surface is turned toward the building platform in the process of 3D printing, show the highest degree of distortion of all of the examined objects. Its direction is parallel to the 3D printing vector.

- The objects, which are oriented in a way that the surface of the first deposed layer to be the smallest possible, show the lowest degree of distortion of all of the examined objects.

- Castable Wax® allows a better accuracy to be achieved during the printing process in comparison to Castable Resin®, but both of them are suitable for dental use as far as 3D printing accuracy is concerned.

- Castable Resin® has mechanical properties which are good enough, even if it isn’t post-cured. Because of the explored shrinkage, the post-curing process can be considered as unnecessary.

- Despite that the structure of the objects affects their mechanical properties, the accuracy of SLP 3D printing technology is not affected.

CHAPTER FIVE

STUDY OF THE EFFECT OF DIFFERENT STRUCTURAL CONFIGURATIONS OF 3D PRINTED OBJECTS, MADE OF CASTABLE RESIN® AND CASTABLE WAX®, TO THE CASTING MOLD PREPARATION PROCESS, WHILE DIFFERENT TEMPERATURE RATES AND INVESTMENT MATERIALS ARE USED

The collected information is entered in a computer database, where it is processed and is exported as charts. The photos, that are taken, are edited by a special software and are presented together with the results.

1. Evaluation of the effect of different structural configurations of printed objects to their investment molds, made of Sherafina® Rapid, during the mold preparation for casting, while a conventional heating rate is used.

After the molds are inserted into the furnace at 25°C, the temperature is raised gradually in correspondence to the examined temperature rate.

When the temperature of 200℃ is reached, the first mold fractures are observed. They engage the surface of some molds with solid objects invested. As 350℃ is reached all of the solid objects crack their investment molds. At this stage only the hollow objects keep their molds intact. **Fig. 38.**

Fig.38. *The fractures over the walls of the molds at 350℃.*

After the 30 min. hold at 350°C, as a result of the thermal expansion and increased gas pressure to the mold walls, the hollow objects also crack their molds, except these with vents. **Fig.39.**

Fig.39. *The results at 350°C. All of the mold are fractured, except these with hollow objects with vent invested.*

During the following temperature raise up to 980°C, no any changes are observed according to the mold integrity. **Fig.40.**

Fig.40. *The experimental molds at 980°C.*

The collected data after ten performed experiments is presented as a chart. **Fig. 41.**

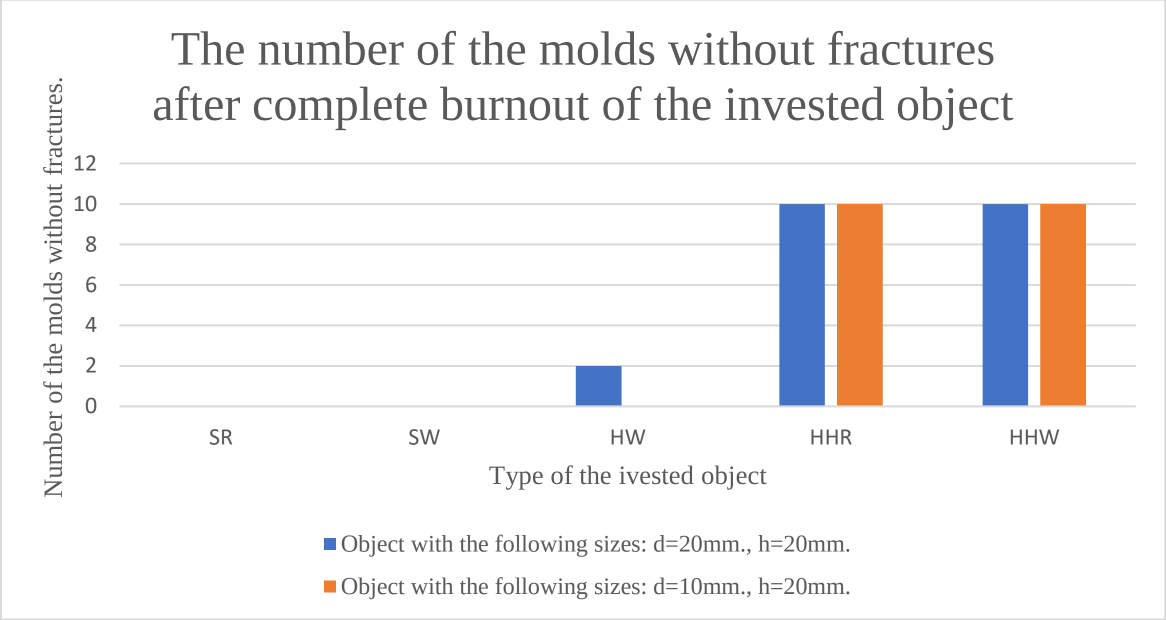


Fig.41. *The collected data after ten experiments. The following abbreviations are used: SW – solid object of Castable Wax®, HW – hollow object of Castable Wax®, HHW – hollow object with, vent made of Castable Wax®, SR – solid object of Castable Resin®, HHR – hollow object with vent, made of Castable Resin®.*

It is apparent that after the burnout process there aren't any intact molds with solid object invested inside. Unfortunately, only 20% of the molds of hollow object keep their intact structure. The results are completely different as far as the molds of hollow object with vents are concerned. The lack of fractures on their wall is observed to 100% of mold. This is a solid evidence that this modification of objects (as hollow object with vent) is successful in the context of the reduction of the pressure to the mold walls.

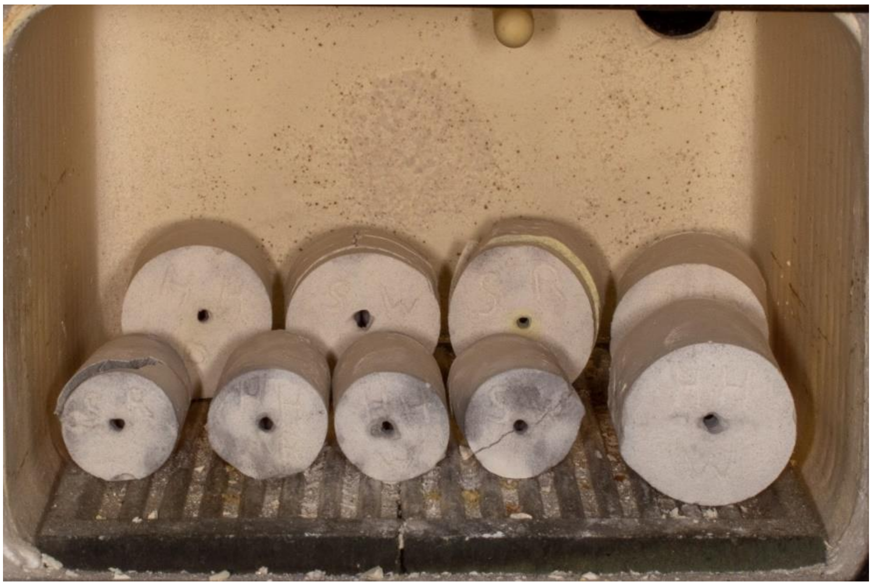
2. Evaluation of the effect of different structural configurations of printed objects to their investment molds, made of WiroFine®, during the mold preparation for casting, while a conventional heating rate is used.

After the molds are inserted into the furnace at 25°C, the temperature is raised gradually in correspondence to the examined temperature rate.

When the temperature of 250°C is reached, the first mold fractures are observed. They engage the surface of some molds with solid objects invested. After 30 min. hold at this temperature level all of the solid objects crack their investment mold. At this stage the hollow objects keep their molds intact. **Fig.43.**

Fig.43. *The observed molds after 30 min. hold at 250℃.*

Druing the next stages of tmeperature rate a fractures of molds of hollow objects are observed but only in a few times in the whole study. No any new fractures are observed till the end of the examined temeprature rate. **Fig.44.**



Фиг.44. *The experimental molds at 1050℃. There aren't any significant diffrences between this stage and 250℃ as far as the mold surface is concerned.*

The collected data after ten performed experiments is presented as a chart. **Fig. 45.**

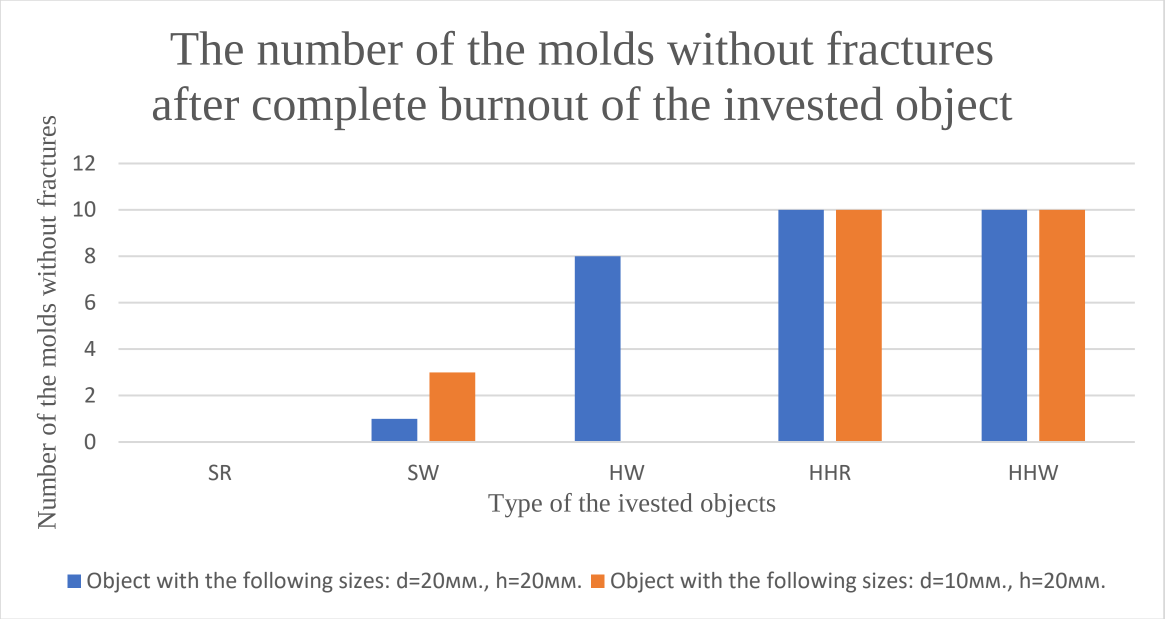


Fig.45. *The collected data after ten experiments. The following abbreviations are used: SW – solid object of Castable Wax®, HW – hollow object of Castable Wax®, HHW – hollow object with vent, made of Castable Wax®, SR – solid object of Castable Resin®, HHR – hollow object with vent, made of Castable Resin®.*

It is obvious that after the burn out process there aren't any intact molds with invested solid object of Castable Resin®. Only 10% to 30% of the solid objects of Castable Wax® keep the integrity of their molds. The molds of the hollow objects without vents keep their intact structure in 80% of the experiments. The results aren't so different when the molds of hollow object with vents are inspected. The lack of fractures on their wall is observed to 100% of the examined molds.

3. Evaluation of the effect of different structural configurations of printed objects to their investment molds, made of WiroFine®, during the mold preparation for casting, while a shock heating rate is used.

The molds are inserted into the furnace at 700°C, acordring to temeperature rate chart. The furnace shouldn't be opened at the first 15 min of the heating procedure because of the risk of injure due to rapid burnig process. Thus, the first results are observed at 900°C.

When the tmeperature of 900°C is reached, all of the molds of solid objects are cracked. During the two of the performed experiments, a mold fracture of a hollow object made of Castable Wax® is observed. And also, a single case of mold crack is observed of a mold with invested a hollow object with a vent inside. **Fig.46.**

Fig.46. *The experimental molds at 900℃.*

During further temperature raise up to 1050℃ and hold of 60 min., there aren’t any new mold fractures observed. **Fig.47.**

Fig.47. *The experimental molds at 1050℃ and after 60 min. hold.*

The collected data after ten performed experiments is presented as a chart. **Fig. 48.**

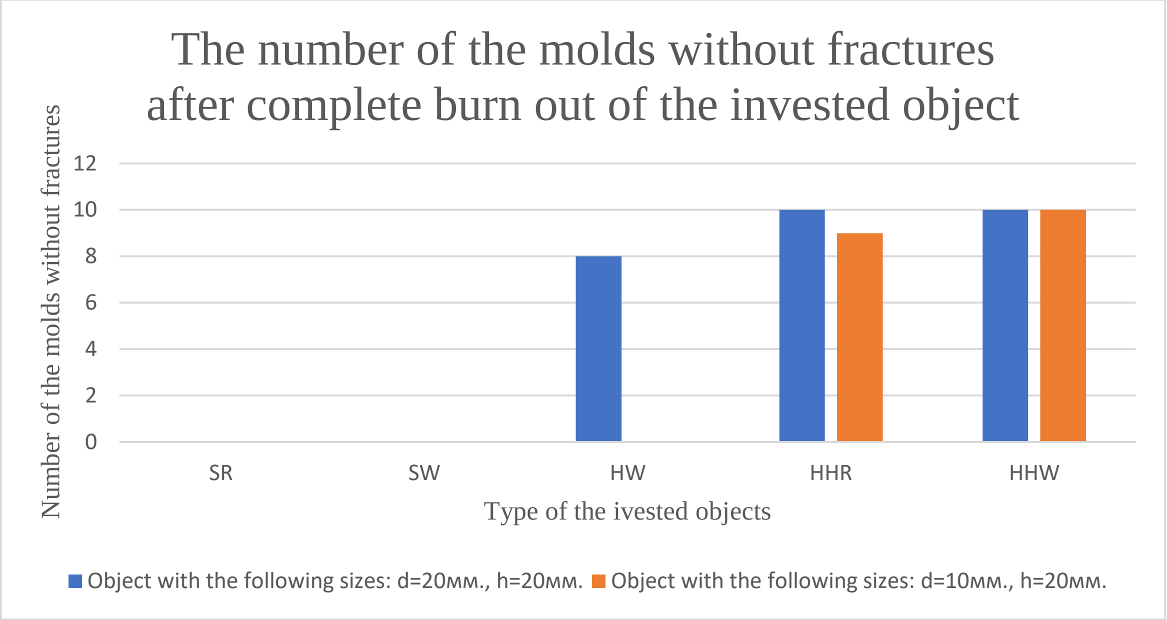


Fig.48. *The collected data after ten experiments. The following abbreviations are used: SW – solid object of Castable Wax®, HW – hollow object of Castable Wax®, HHW – hollow object with vent, made of Castable Wax®, SR – solid object of Castable Resin®, HHR – hollow object with vent, made of Castable Resin®.*

When the molds made of WiroFine® and are heated by a shock rate are examined, it is obvious that all of the mold with a solid object invested are fractured at the end. When the investment molds of the hollow objects are observed, the following result is achieved: 80% of all molds of the mention type keep their structure and are suitable for casting after the heating process. Finally, all of the observed molds of the hollow objects with vents are intact after the preparation procedure.

6. Discussion

The results that are achieved completely confirm the initial statement. Because of the influence of object's weight to the generated pressure to the mold walls, two new configurations of object structures are achieved - hollow objects and hollow objects with vents. The main purpose of this modification is the reduction of object's weight while the volume is kept. When the objects are 3D printed as a hollow without vent, a little amount of uncured resin is arrested inside the object structure. Thus, the reduction that is achieved to these objects is between 55% and 60% in comparison to the solid. When the modified hollow objects have vents, they make possible the elimination of uncured resin by rinse with isopropyl alcohol. Thus, the achieved weight reduction is around 70%. So, the less the weight is, the less the amount of the gas is. At the same time the cavity inside the object allows it to expand inward by reducing the stress against the mold walls.

When the solid objects are examined the result is clear. As a result of the generated pressure to the mold walls, the mold cracks, regardless of the temperature rate or the characteristics of the investment material. When the hollow objects with vents are observed, the result is completely different, their structure allows inward expansion directed to the internal cavity, and as a result they keep their mold integrity successfully. The mechanism of thermal elimination of the hollow objects without vents is more complicated. While the thermal expansion is presented as usual, the generated gas (as a result of sublimation) increases the internal pressure into the object. As a result, the increased pressure interferes the internally directed expansion and the forces to the mold wall become more intensive. This results in mold crack in a few of the performed experiments.

In order to be examined the effect of the object's volume to the examined processes, two types of samples are fabricated – a type with diameter 20mm. and height 20mm. and another one with diameter 10mm. and height 20mm. These sizes are selected because the smaller group of objects have almost the same volume as two- or three-unit bridge and the group of the bigger objects provide a chance for examination of more severe conditions. Actually, a significant difference between these two groups is not observed.

The casting conditions are also affected by the characteristics of the investment material. One of the examined investment materials is Sherafina® - Rapid (SHERA®), which has low to moderate compressive strength. In this context, it is necessary the invested object to be 3D printed as hollow with vent, in order to be achieved a cast with good properties. Otherwise, the possibility of mold crack is around 80% to 100%.

The technology that is prescribed from Formlabs™ for thermal elimination of the initial prototype is unacceptable when relatively large objects are burned out, due to mentioned phenomena. Regardless of the temperature rate, the invested objects should be 3D printed at least as hollow objects and if it is possible a vent is recommended.

In order to optimize the casting process some further researches can be made about a modification of the temperature rates for mold preparation, the characteristics of the pattern materials or investment materials.

7. Conclusions:

- The thermal expansion coefficients of Castable Resin® and Castable Wax® are higher than the coefficient of thermal expansion of the examined investment materials.
- The ability of the explored materials to sublimate and the generated gas are factors that generates additional pressure against the mold walls.
- The weight reduction of the invested object with certain volume results as a considerable decrease of the pressure to the mold walls.
- A different from the prescribed from Formlabs™ investment materials can be used in burnout procedure of Castable Resin® and Castable Wax®, but only after a specific modification of the invested objects.
- There isn't any considerable difference between Castable Wax® and Castable Resin®, when the available mold fractures are observed.
- The temperature rates prescribed from Formlabs™ for thermal elimination of the initial prototypes are unacceptable, when the invested prototypes are 3D printed as solid objects and volume is equivalent to two- or three-unit bridge.
- In order to be reduces the generated pressure of the emitted gas and the thermal expansion during the thermal elimination process, the invested objects should be 3D printed as hollow with vents. This modification prevents the investment molds from crack and allows investment materials with compressive strength from 5,5 MPa to 11 MPa to be used.

CHAPTER SIX

CASTING CONDITIONS IMPROVEMENT BY SOFTWARE OPTIMIZATION 3D PRINTED PATTERNS DESIGNED FOR CASTING DENTAL ALLOYS

1. Casting conditions improvement by digital planning and 3D printing of crown patterns and a custom-made sprue system together as a single object.

The sprue system is 3D printed successfully by using the described method. **Fig.49.**

Fig.49.*The crown patterns and casting system that are produced by SLP technology. After supporting structures removal, the digitally generated casting cone can be used as a base for mounting of the casting system to the prefabricated casting cone.*

After cleaning the remnants of uncured resin by isopropyl alcohol, the supporting structures are removed and the sprue system is prepared for investing. **Fig.50.**

Fig.50. *The spue system is properly aligned and fixed to the casting cone.*

It is apparent that the ball-shaped reservoirs will be located around the central thermal zone of the future mold. In addition, the patterns are situated around the most favourable zones. The sprue system has the same configuration as the digitally planned. As a conclusion the parameters that are set digitally are represented in the 3D printed object in an absolute precise way.

2. Casting conditions improvement by digital planning and 3D printing of crown patterns, custom-made sprue system, casting ring and casting cone together as a single object.

The sprue system, the casting cone and the casting ring are 3D printed as a single object successfully by using the described method. After cleaning the remnants of uncured resin by isopropyl alcohol and supporting structures removal, the sprue system is ready for investing without any additional preparation. **Fig.51.**

Fig.51. *The object that is 3D printed consists of: a casting cone, a casting ring and a casting system, which are materialized as a single object*.

The removal of some internal supporting structures, located between the sprue system and the casting ring and cone, may be difficult. Actually, these structures may be left and they may serve as vents during the burn-out process.

This approach allows selection of the most suitable casting conditions, when the patten material, the characteristics of the investment material, the configuration of the patterns and the casting technology is observed.

3. Discussion.

Due to variety of conditions that affect the casting process, it is considered as an inaccurate way of crowns fabrication. In order to reduce the possibility of fail and any inaccuracy, all of the components of the sprue system should be arranged in a specific way. Digital creation of a sprue system allows all the parameters to be set precisely as well as the central thermal zone and the most favourable position of the patterns to be located with great accuracy.

The most commonly used material for casting system fabrication is the wax. Unfortunately, it has the ability to flow under prolonged mechanical interaction or due to temperature rising. This is a factor that may cause any kind of deformations of the sprue system during the fabrication process and afterwards. When the whole casting system is made of resin, the risk of deformation is much less, due to its mechanical properties and thermal resistance.

Usually in daily dental laboratory practice a different number crowns or dentures which also have a specific volume should be fabricated. This requires a huge amount of different casting rings to be available in the dental laboratory. Thus, a new approach for digital sprue system and casting ring fabrication is developed. It allows fabrication the of a casting ring with custom-selected and optimal dimensions, which corresponds to the configuration of the casting system. Then the casting ring and the sprue system are 3D printed as a single object, which also eliminates the usage of any additional materials. The main disadvantage of this approach are the supporting structures that are generated between its components which are difficult to remove.

The digital approach in sprue system fabrication is a time-saving method which is more accurate and reliable than the conventional one.

4. Conclusions:

- Digital approach in sprue system fabrication allows absolutely accurate arrangement of the system components.

- 3D printed sprue systems are more resistant to any interactions compared to those that are conventionally made.

- The digital approach in sprue system fabrication is a time-saving method compared to the conventional one.

- The digital approach in sprue system fabrication allows proper selection of all the parameters of the system components as well as the configuration of the casting ring and cone.

- The fabrication of the sprue system, casting ring and casting cone as a single object, improves the casting conditions and provides more reliable results.

SUMMARY

1. Considering the variety of materials for pattern fabrication and their specific physical properties and in order to receive a cast with good properties, some modifications of the production process have to be made. The waxes are an exception.

2. Despite the examined materials leaves some ash content after burnout, its amount is little enough to provide good conditions casting conditions.

3. The temperature related physical characteristics and the amount of the ash content that leaves Castable Resin®, specify it as suitable for use in dental medicine.

4. Castable Wax® allows a better accuracy to be achieved during the printing process in comparison to Castable Resin®, but both of them are suitable for dental use as the 3D printing accuracy is concerned. The orientation of object plays a crucial role for the accuracy of SLP 3D printing technology.

5. Castable Resin® has mechanical properties which are good enough, even if it isn’t post-cured. Because of the observed shrinkage, the post-curing process can be considered as unnecessary.

6. Although the structure of the objects affects their mechanical properties, the accuracy of SLP 3D printing technology is not affected.

7. A modification of the printed relatively large objects (made of Castable Resin® and Castable Wax®) to hollow object with vents is recommended, in order to be achieved a good result of the casting process. In case that the modification is missed, the result of the casting process become more unstable.

8. Digital approach in sprue system fabrication allows absolutely accurate arrangement of its components. In addition, its fabrication of resin-based material makes it highly resistant to any mechanical and thermal interactions. Thus, the method may be described as reliable and time-saving method for pattern fabrication.

9. The fabrication of the sprue system, casting ring and casting cone as a single object, improves the casting conditions and provides more predictable and reliable results.

CONCLUSION

The present research is prompted by the rapid development of dental materials and production technologies and during the last few decades. In past few years the additive technologies become more commonly used in daily dental practice. Unfortunately, there are fundamental issues that still remain unsolved.

The research examines the process of denture prototypes fabrication by SLP technology and the related to them conditions for cast dentures production. The casting is a process that depends on a variety of factors including characteristics of the pattern material, also the investment material or the temperature rate of mold heating. Thus, the temperature related physical changes of objects made of different materials are inspected by observing their specific featured, and resolving the related issues.

In addition, some of the main features of SLP 3D printing process are inspected. The effect of different orientation and structure of the printed object to the production accuracy is observed. In this context, a method for digital optimizations of object's structure to a hollow with vent is developed. The suggested hypotheses are examined in close to the real conditions and as a result are confirmed. Furthermore, a new approach of digital planning and further materializing of a sprue system, casting cone and ring as single object is suggested.

The results of the entire research will enrich and update the available information about the process of denture pattern 3D printing and further casting process. A new approach, which optimize the work process at the dental laboratory and dental office is suggested.

CONTRIBUTIONS

Contributions of scientific and applied nature:

- **Contributions of original nature:**

1. The temperature related physical changes of different materials (Pattern Resin LS™, C-cast, CAD/CAM wax, Castable Resin®), used for fabrication of patterns for casting from dental alloys, are examined.

2. The better accuracy of SLP 3D printing process is proved, when Castable Wax® is used instead of Castable Resin®.

3. It is proven that the post-curing process of Castable Resin® objects is not mandatory or even useful, because it may cause an object deformation.

4. The role of object’s weight (for those made of Castable Resin® or Castable Wax®) to the generated forces against the mold wall during the process of thermal elimination is examined. Thus, a modification of objects structure as hollow with vents is suggested.

5. It is proven that the object of Castable Wax® and Castable Resin® can be invested by using different than the prescribed investment materials, as Sherafina® Rapid for instance.

- **Contributions of a confirmatory nature:**

1. It is confirmed that the material Castable Resin® is suitable for denture pattern fabrication, when the production accuracy and the amount of ash content are examined. It is also suggested a proper temperature rate and investment material to its use.

2. It is confirmed that Castable Wax® and Castable Resin® allow 3D printing of objects with great accuracy. The recorded deviations are around 25,27 μm. for Castable Resin® and 13,87 μm. for Castable Wax®.

3. The role of direction of 3D printing process to the production accuracy is confirmed.

Contributions of applied nature:

- **Contributions of original nature:**

1. A method for digital planning and 3D printing of a sprue system, made in accordance to the parameters of prefabricated casting ring and casting cone, is suggested.
2. It is developed a new method for digital planning of a sprue system, casting ring and casting cone and further 3D printing as a single object.

SCINETIFIC ARTICLES RELATED TO THE DISSRETATION

1. Penchev P. Temperature Related Physical Changes of Different Materials for Fabrication of Patterns for Casting from Dental Alloys. International Journal of Science and Research. 2020;9(10):1466 - 71. doi: 10.21275/SR201024131835.
2. Penchev P., Katsarov S., Digital casting cone and sprue fabrication for 3D printed patterns designed for casting dental alloys., Journal of Medical and Dental Practice (Medinform), 2020; 7(2):1190-1263.
3. Katsarov S., Penchev P., Laboratory assessment of the accuracy of two different resins designed for 3D printing for cast metal frameworks and suprastructures., Clinical Oral Implants Research, 2020; 31.