Review
by
PROF. STEFAN IVANOV SIROMASHKI, DMD, PHD

regarding the dissertation for conferment of the educational and scientific degree "PhD" to Dr. Preslav Plamenov Penchev scientific specialty - 03.03.03., entitled:

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

Scientific supervisor: Assoc. Prof. Stoyan Georgiev Katsarov, DMD, PhD - All necessary administrative documents are presented according to the regulations for conferment of the educational and scientific degrees (PhD), The review is prepared in accordance with the requirements of the Law on the Development of the Academic Staff Bulgaria and the Regulations for development of the Academic staff of the Medical University - Varna

Biographical data

Dr. Preslav Plamenov Penchev was born on April 30, 1991 in the city of Ruse. In 2010 he graduated form the Mathematical High School "Baba Tonka" in Ruse, specialty “Informatics”. In 2016 he graduated from Mecial University Prof. Dr. Parashkev Stoyanov - Varna, specialty “Dental Medicine”. From 2016 until now, after passing a competitive exam, he started working as an assistant in the Department of Prosthetic Dentistry, FDM, MU - Varna. Develops dissertation entitled:”3D Printed Prototypes of Cast Metal Denture Frameworks Fabricated by Laser Stereolithography Printer”.

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Dissertation structure

The dissertation is written on 160 pages, including the appendices. It is illustrated with 78 figures and 34 tables. The bibliography contains 180 sources, as 20 of the them are in Cyrillic and 160 in Latin.

Chapter Six

A brief historical overview

In the 80s of the twentieth century, computer technology made a great progress, which created the preconditions for application in dentistry. Dental work is digitizing faster than expected. CAD / CAM technology solves many issues, allow laboratories to be more productive and able to offer greater precision, a greater variety of products, and to introduce more and more various materials. Computer-aided design was introduced to dentistry by Francois Duret.

In 1980, Dr. Werner Mormann and Marco Brandestini introduce the computer-machine design and fabrication of dental prostheses, which design and abilities are improving the each following year. This processing is known as CAD / CAM (Computer Aided Design - Computer Aided Manufacturing). These are two programs that are interconnected and manage the CAD / CAM-systems. They are based on three main processes; Gathering information, Processing information, Fabrications. This technology is widely used in everyday dental and laboratory practice. With this technology, irreversible losses are over 50%. Therefore, new technologies are invented.

A new direction in dental medicine is the technology of denture construction layer-by-layer. In 1986, Hill, CW developed and patented the process of stereolithography - the first technology for 3D printing The materials used for this technology are photopolymerizing composites based on polymethyl methacrylate (PMMA) and various resins.A laser beam or other type of light source (SLA) can be used. The most commonly used are: the selective laser polymerization (SLP, Lazer-SLA, digital light projection (DLP_SLA) - MSLA- (MASKRD_SLA). Regarding (SLA), two different methods are known: right-side sterolithography and the other - Upside-Down stereolithography. During the process of stereolithography concentrated UV light is focused on the surface of the vat and directly on the surface of the liquid.In some variations of this process a liquid polymer is used, as each layer is polymerized under the action of the light beam. At each step, a layer of monomer is polymerized or crosslinked. The part is built layer by layer until a complete object is obtained (75,154,159,170,171)

The accuracy which is the main characteristic of the stereolithographic technology is between 50 µm. up to 250 µm., thus providing a relatively smooth surface of the bult object. Along with this, a wide variety of materials have been developed for use with the devices with this technology integrated. Last but not least, the devices which are based on this technology are significantly cheaper than most devices which adopt any different additive technology (75,171).

In the 1980s, Stephen Scott Crump created an additive method for fabrication (FusedDepositionModeling - FDM). The process based on the extrusion of filamentary thermoplastic material. The technology consists of the following structures: a nozzle, from which injects a building materiaл, while a another nozzle extrudes material for the support structures and also a building platform where the object is created. The nozzle moves along the x and y axes, and the platform along the z axis, i.e. in the vertical direction. Each each mobement in verticall direction is equal to the thickness of one layer extruded material. In the process of construction, each layer adheres to the previous one. This technology uses a huge variety of materials such as: acrylonitrile butadiene styrene (ABS), polycarbonates, polycaprolactone, polyphenyl sulfones, and also waxes.

In the mid-1980s, Dr. Carl Deckard and Dr. Joe Beeman developed a new additive method for selective laser melting and selective laser sintering. Selective laser sintering refers to superficial melting of the particles of the building material Selective laser melting refers to a complete melting of whole building particles during the printing process. In this way, the details are created by selective laser melting.

Technology based on inkjet printing

Inkjet printing technology different to the ink liquids - various adhesives, aqueous solutions of dyes, a suspension of ceramic particles. The liquid building material after leaving the nozzles turns into a solid state. In this technological process a liquid light curing resin is used, which is cured by ultraviolet light. There is an inkjet machine devices have the following structure: a tank for the building material, roller for spreading a new building material, ink jet head for delivery of adhesive during operation, which can move up and down (along the z axis) and is located in a working chamber, where the process of layer-by-layer construction takes place. The process of 3D printing begins by lifting the piston from the bottom of the tank by pushing a certain amount of powdered building material. A special roller pushes it to the working chamber and spreading it on the surface of the platform. The inkjet head moves and selectively releases a liquid adhesive on the spreaded material by building a layer of the manufactured part. The work platform then moves down a distance equivalent to the thickness of one layer of the bult object. The piston from the tank is raised again, and the roller delivers a new amount of building material, which is positioned over the previous layer.

In the Brief Historical Review Dr. Penchev examines in great detail and at the modern scientific level the technological process of casting and the relevant materials:

-Waxes used for dental purposes,

- Modeling plastics used in dentistry

-Refractory ivestment materials:

a) - gypsum, b) phosphate, which should be mixed with water, c) phosphate, which should be mixed with a special liquid, D) ethyl-silicate, e) magnesium-zirconium.

- Investment materials for casting:

a) precious alloys, b) crowns and bridges, c) model casting, d) fine, e) pressing of ceramics, f) refractory stumps g) injection molding of thermoplastic materials h) conventional heating, i) speed (shock) heating

- Development of a casting system

- Metals and alloys used in dentistry

- Casting – An overiew of the process

Chapter Two
Aim and Tasks

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.

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

For the purpose of the study of **task 1** four identical cylindrical 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 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 25°C, as the temperature is raised by от 9°C/min and is hold by 10 min at each 50°C.

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. They also have different structure and orientations and are made of Castable Resin and Castable Wax.

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

The mechanical and physical prpperties of Castable Resin and Castable Wax are examined. 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. 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 heated by using the specific temperature rate for the examined investment materials (shock and conventional heating rates)

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.
- six direct sprues, diameter 2,5mm. 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 and are situated in a position to be within the thermal zone of the mold. They are set to be 5mm. in diameter.
A special tool called “Measure tool” is used in order to be achieved more precise results. 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.

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.
The examined objects are inserted into a furnace at 25℃ ℃, as the temperature is raised by от 9℃/min up to 100℃ - no any changes reported
- At 150℃ - CAD/CAM Wax sepecimen’s edges start looking round and it’s the surface has a mat texture.
-At 200℃ - 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. After the 10 minutes hold, the CAD/CAM wax sample is already melted and starts boiling.
-At 250℃ - 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. It becomes darker, because of the burnout of some resin components.
- At 300℃ - The CAD/CAM wax sample evaporates rapidly. 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.
- At 350℃ - The C-cast pattern becomes porous, without any visible volumetric changes. The C-cast specimen become porous. 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 reported.

- At 400℃ - 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.
- Between 450℃ - 550℃ - A rapid burning process is apparent. At 550℃ 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.

- At 600℃ - The C-cast® and Pattern resin LS™ samples show no residual ash remnants. In contrast to them the CAD/CAM wax and Castable Resin® samples leaves a little amount of residuum.

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

After the burnout process, the sample of Castable Resin® and CAD/CAM left a little amount of ash content.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. The reported weight of the residuum of the Castable Resin® is 0,001g.

Conclusions based on the study of task 1

The CAD / CAM sample w. melts at 200 ℃. and leaves a small amount of ash residue.
The Pattern Resin LS sample melts at about 400 ℃, as it almost doubles its volume and burns without leaving an ash residue at 600 ℃.
The C-cast sample burns without leaving an ash residue at 600 ℃ with minimal expansion.
The Castable Resin sample sublimes when heated to a liquid state

Chapter Five
Task 2

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

The obtained data were processed using the IBM SPSS®, IBM ™ software. The achieved results clearly show the influence of the direction of orientation of the objects during the printing process. The details, which are positioned with a wide base to the printing site, show significant deformation in size. The first layer of the object is extremely graceful and easily deformed under the action of the weakest mechanical impacts. To avoid this problem, it is necessary for the first layers to have the smallest possible area. Larger deviations are observed in the details with a linear angle to the site.

Conclusions based on the study of task 2.1

The details, which are positioned with a wide base to the printing pad, show significant deformations in size. The first printer layer should have a minimum surface area, which leads to small deviations. Castable Wax® resin provides conditions for obtaining more accurate details compared to Castable Resin. Both resins are suitable for the production of prosthetic structures according to the printing accuracy.

- Castable Resin® material has good mechanical properties, even without additional polymerization. When the shrinkage is observed, any additional polymerization process of Castable Resin® is not preferred. Although the specimens change their mechanical properties after the software modification to hollow objects, the accuracy of printing is not affected.

Chapter Six
Task 3

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.

Photos of the molds before the burning process are presented
- When 150 ℃ is reached there aren’t any cracks and significant mold changes reported.
- At a temperature of 200 ℃, the first fractures are reported. They ate located on the surface of the mold with invested object of Castable Resin.
--At a temperature 300 ℃ no any new changes are observed.
- At a temperature of 350 ℃, There are some new cracked molds. Due to the gas pressure after holding the temperature of 350 ℃ for 30 minutes, cracks and even destruction of the molds with the solid and hollow bodies are reported.

- At a temperature of 450 ℃ liquefaction of the used resins is reported
- After a temperature of 450 ℃ to 600 ℃, rapid burning of the esamined specimens is observed, a certain amount of ash residue is observed.
- At 980 ℃ no any new changes are reported. , No fractures are found to The molds with invested hollow objects with vents. This is a prerequisite for obtaining quality castings. It has been observed that there are no mold with solid objects invested keep their integrity after the burnout process.

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.

The molds are inserted into the furnace at room temperature (25 ℃), after that it rises by 5 ℃ / min. up to 250 ℃. When this temperature is reached, the first fracture on the surface is registered.. After 30 minutes at this temperature, fractures appear over the surfaces of all the molds with invested solid objects, because of a large amount of emitted gases. At temperatures above 570 ℃ a process of rapid burning is reported. As a result of the burning porcess the volume of the ivested objetcs decreases rapidly.
In this study, it was found that solid objects preserve the integrity of the molds only in 10% to 30%., if they are made of Castable Wax®. There aren't any observed fractures of molds with hollow objects with vents invested. At the same time the hollow objects without vents crack their molds in 80% of the tests.

Chapter Seven
Task 4
Casting conditions improvement by digital planning and 3D printing of crown patterns and a custom-made sprue system together as a single object.

After removing the support structures, the casting tree is placed to the prefabricated casting cone. The quality of the cast depends on many factors. The software allows accurate measurement of all the parameters of the casting system, especially the accurate determination of the central thermal zone of the mold, which affects the quality of the casting. The most commonly used material for a casting system fabrication is the wax. It can be easily deformed by causing minimum load and temperature rise. 3D printing of a casting system made of 80% resin and only 20% wax results in good castings. The positive qualities of the waxes and the resins used in a single composition, demonstrate better physical and mechanical properties then the conventional waxes. A reliable and predictable result is always achieved, when they are used.

Conclusions

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.

Contributions

- **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:

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.

Dissertation Summary

The content and quality of the abstract meets all the requirements of the Law for the Development of the Academic Staff in the Republic of Bulgaria. It is a miniature copy of the dissertation.

Critical remarks

Regardless of the indisputable qualities of the thesis of Dr. Penchev I want to make make some critical remarks.

1. The title of the dissertation is not very appropriate
2. The discussion with the results of other authors is missing.
3. The names of the experimental objects can be met with different names.

These critical remarks could not reduce the good qualities and scientific merits of Dr. Penchev's dissertation.

Conclusion

The dissertation has an original contribution to science and meets all the requirements of the Law for the Development of the Academic Staff in the Republic of Bulgaria.

In his dissertation, Dr. Penchev considers a contemporary problem in the field of prosthetic dentistry. A detailed research is conducted considering the casting process issues and the temperature related changes of the materials for pattern fabrication. He offers a recipe for improving the quality of the modeling waxes. He admires the opportunities for fabrication of cast metal structures by stereolithography by the method of selective laser polymerization. Important conclusions and contributions have been made to clinical practice and theory.

Dr. Penchev has good theoretical and professional knowledge skills in Prosthetic Dentistry, demonstrating high skills for independent research, which is evident in the dissertation.

He creates his own methods in the dissertation, which will inevitably increase the quality of dental prosthetic structures. The dissertation contains scientific and applied results, which represent an original contribution to dental practice and theory. The dissertation is mainly a personal work of Dr. Penchev.

Due to the above, I confidently give my positive assessment of the research conducted in the dissertation and the scientific results achieved and contributions in the field of dental medicine. As a member of the Honorable Scientific Jury, I will vote convincingly with "YES" for the conferning of educational and scientific degree "PhD" to Dr. Preslav Plamenov Penchev

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