CUSTOMIZED MEDICAL APPLICATIONS OF SELECTIVE LASER MELTING MANUFACTURING

Sorin Cosmin COSMA[1], Nicolae BALC[1], Dan LEORDEAN[1], Marioara MOLDOVAN[2], Mircea DUDESCU[3] and Cristina BORZAN[1]

ABSTRACT: Selective laser melting (SLM) is widely gaining popularity as an alternative manufacturing technique for complex and customized implants. This technique has eliminated the constraints of shape and mechanical properties making it possible for fabrication of implants that are conform to the physico-mechanical requirements of implantation. The object of this article is to combine customized dental implants manufactured by SLM with bioactive surface treatments. After fabrication, the implants were coated in modified SBF solution with biodegradable β-TCP and Chitosan, respectively acid etching followed by grit-blasted with apatite. Mechanical studies were developed initially to determine ultimate and yield tensile strength and Young modulus obtained with specific process parameters on standard samples. Finally, the implants were microscopically analyzed and measured the roughness. The purpose of this research was to improve the design and manufacturing process of novel customized parts for dentistry.

KEY WORDS: screw vent, blade implant, roughness, surface treatments, process parameters

1 INTRODUCTION

Additive Manufacturing (AM) technology applications are very diverse and can be used in many fields, from industry to design or medicine. Applications of AM technologies in medicine are reported since 1994 (Kruth, 2005). These applications have led to the development of customized implants that are physical prosthetic models made for each individual case in order to accurate reconstruction of bone structure (Berce, 2005), (Leordean, 2015).

In recent years, the SLM technique part of AM, has become a practice in the area of customized medical implants from different biocompatible alloys like Ti, CoCr or Ni (Biemond, 2013). In order to show above explained benefits of implants made by SLM, two case studies have been developed with customized parts. This technology enables manufacturing of implants that combine solid and porous zones (lattice structures). By means of 3D-CAD software, these lattice structures can be designed and manufactured with the desired pore size, morphology, well-interconnected porosity and gradual transition from solid (body implant) to porous.

[1]Technical University of Cluj-Napoca, Department of Manufacturing Engineering, 103-105 B-dul Muncii, Cluj-Napoca 400641, Romania
[2]Raluca Ripan Institute for Research in Chemistry, 30 Fantanele Street, Cluj-Napoca, Romania
[3]Technical University of Cluj-Napoca, Department of Mechanical Engineering, 103-105 B-dul Muncii, Cluj-Napoca, Romania
E-mail: sorin.cosma@tcm.utcluj.ro

The SLM process provide with success the obtaining of porous metallic implants, and the pore size resulted could allowed the necessary nourishing to cell survival, proving that pores and channels form a high interconnectable network represented by the osseointegration and osteoconduction feature of the porous titanium (Biemond, 2013). The main objective of this study was to design and manufacture novel customized implants via SLM and to analyze the results. In addition, to improve the surface quality of parts, after SLM fabrication, it was applied different bioactive surface treatments and finally the surfaces were microscopically analyzed by SEM and EDX/EDS.

2 MATERIAL AND METHODS

2.1 Material

The material used for manufacturing was especially gas-atomized Ti powder named TILOP45 provided by Osaka Titanium Technologies. This powder has a medium 45μm particle diameter, the melting point around 1670°C, 4.51 g/cm^3 density and it can be include in category of Ti Grade I. Pure Ti was used as a biomedical replacement for Ti_6Al_4V alloy because doesn't contains vanadium, an element that has demonstrated cytotoxic outcomes when isolated (Palanuwech, 2003) and pure Ti is often used in the body is due to titanium's biocompatibility with surface modifications and bioactive surfaces.

2.2 Equipment

SLM REALIZER 250 system (MTT Technologies, Germany) uses selective laser melting technology and provide 3D CAD data as a digital information source and energy in the form of a high-power laser beam (200 W maximum power) to create three-dimensional metal parts by fusing fine metallic powders together. Such as all the AM processes, a 3D-CAD data file converted to the *.stl* format is sliced in layers of a definite thickness. Layers were scanned using a continuous laser mode according to a zig-zag pattern, which was alternated by 90° between each layer. Therefore, the extent of powder melting in each scan decides the achievable porosity in the final part depending on laser powder (*L*), scan speed (*v*), hatch distance or scan line spacing (*h*, usually 0.1-0.12 mm) and layer thickness (*t*, usually 50 μm). The total energy input per volume of each scan (*E*, Equation 1) as a function of processing parameters was evaluated from (Bandyopadhyay, 2010):

$$E = \frac{L}{v * h * t} \quad [\mathrm{J/mm^3}] \qquad (1)$$

All these process parameters were edited in RDesigner and REditor software's and scan speed was set up through Point Distance and Expose Time process parameters. All the parts that will be featured in this article were designed in SolidWorks software.

2.3 Dimensional measurements and roughness

After the parts were produced by SLM process, it was measured with a digital caliper (Absolute Digimatic IP67 Mitutoyo, ±0.02 mm accuracy), according to ISO 13385-1:2011. The dimensional error D_e [%] was introduced in order to perform an analytical study of the accuracy (Equation 2). In this equation N_d and M_d represent the nominal and respectively the measured dimension.

$$D_e = \left(\frac{M_d - N_d}{N_d} \right) * 100 \quad [\%] \qquad (2)$$

In SLM technology, the surface quality is not only a primary concern to the users, but also a key issue in completion of the component during the fabrication. The obtainable surface quality of SLM parts is considered as one of the major drawbacks of the process and has been the subject of many studies in recent years (Liu, 2004), (Pyka, 2013). The roughness was measurement using a digital apparatus for roughness (Mitutoyo SJ-2010) according to ISO 4287:2001, where R_a is arithmetic average of absolute values and R_z is calculated by measuring the vertical distance from the highest peak to the lowest valley. Outer boundary is the process parameter for controlling the surface roughness and the Table listed below do not contain this parameter only the measurement results (in order to not complicate).

2.4 Mechanical properties

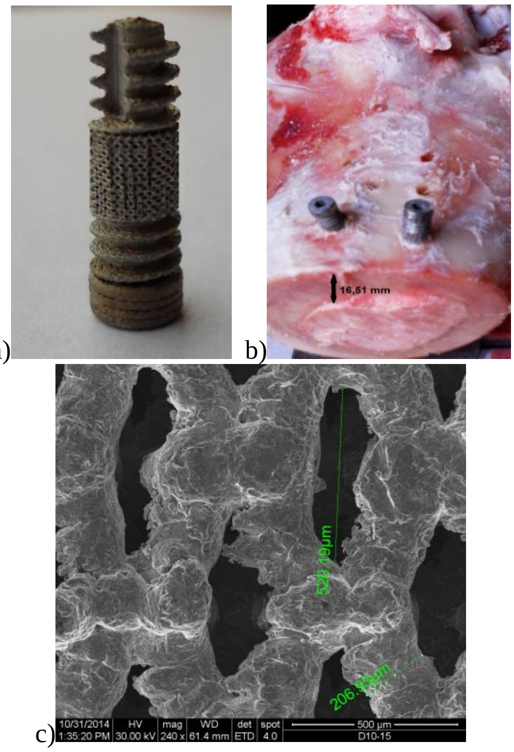
Tensile properties were performed according to ISO 6892:2009 on several sheet standard samples fabricated using SLM technology with different process parameters. Ultimate and yield tensile strength ($\sigma_{UTS,}$ respectively $\sigma_{0.2}$) and Young modulus (E_Y) were achieved by Instron 3366 equipment with extensometer Instron 2620-602. The cross-section of the parts was rectangular and other similar tests were developed in earlier researches (Muresan & Balc, 2011), (Muresan, 2011), (Leordean, 2011). Firstly, standard samples were fabricated with various process parameters whereupon were mechanical tested. **S**econdly, with the same manufacturing conditions were fabricated the customized parts. Ti was used for research due to its excellent properties such as high corrosion resistance, low modulus, high fatigue strength, low density (lower than most common metallic materials) and good mechanical properties for medical implants.

3 RESULTS AND DISCUSSION

3.1 Case study: Screw Vent Implants with Open Porous Structures

A special attention has been given globally in recent years to osseointegration of Ti implants and their transformation into bioactive using different methods. Different implant body designs are available in implant dentistry (Misch, 1999) and they may be categorized as a cylinder type, screw type or blade, and it can be seen in Figure 1 or 3. Since P.I. Branemark published his studies (Branemark, 1983), continuing dental and orthopedic research has focused on various techniques for enhancing bone apposition to implanted Ti surfaces. Also, the most common endosseous implants have usually shaped like a screw or blade, and are placed within the jawbone.

M. Collins et al. have developed and manufactured by conventional technologies (CNC machines) a new design of dental implant to increase the ingrowth osseointegration (Collins, 2012). The implant is a tapered, multi-threaded, endosseous design similar to its predicate, the tapered screw-vent implant, but modified with a trabecular metal material in midsection. The coronal section features cervical micro-grooves and internal hex, friction fit connection, and the apical section features self-tapping threads (Collins, 2012).



a) b) c)

Figure. 1 Screw vent dental implant: a) M_1 implant after SLM manufacturing, b) M_1 implants during RTT into bovine femur bone, c) SEM image of macroporous structure (cord-support) of M_1, 240x magnification

A key problem of custom-made dental implant is manufacturing of complex shapes. With the ever increasing demand for complexity and accuracy, traditional machine tools have become ineffective for machining them. Commercially standard dental implants provide only limited options for implant length, diameter, and thread parameters and cannot completely meet the requirements for all individual oral conditions, so custom-made implant is desirable. Thus, customized dental implants tailored to individual patients not only preserve more hard and soft tissues but also reduce rehabilitation time, opening a promising prospective for implant dentistry (Chen, 2012), (Figliuzzi, 2012).

So, starting from M. Collins and other researches (Chen, 2012), (Figliuzzi, 2012), (Cosma, 2014), (Jividen, 2000), this case study presents two customized screw vent implants with open porous area manufactured by SLM and the novelty of these implants is the design and manufacturing method. It was developing dental implants (M_1 and M_2) with macro-porosity (lattice structure shape) and Figure 1a illustrates this endosseous screw implant with V form of the thread, micro-grooves shapes and open porous area. Using RDesigner software, in the midsection of the implant was designed an open porous structure (lattice structure). The design strategy was integrated into monolithic layer building in the SLM material file and 24 pieces of these implants was manufactured by SLM technology (12 pieces of M_1 and 12 pieces of M_2 screw vent implants).

The difference between M_1 and M_2 was the process parameters of fabrication shows in Table 1. In midsection of implants, a lattice structure was manufactured with 1.00 mm depth. The cord-supported of lattice structure has a diameter around 200 μm and the pore size is between 150-520 μm (Figure 1c). In general, implants with pore sizes in the range of 100 to 500 μm are suitable for bone ingrowth and was reported direct connectivity of macropores with bone (Bandyopadhyay, 2010), (Esen & Bor, 2007). It has also been suggested that the degree of interconnectivity is more important for new bone formation than the pore size itself and this lattice structure manufactured on midsection of implants has interconnections pores (Lu, 1999). The

Table 1. Characteristics of dental implants fabricated by SLM

Properties		**Screw vent**		**Blade**	**Titanium, Typical Required***	**Cortical bone****
		M_1	**M_2**	**M_3**		
Process Parameters	Scan Speed [mm/s]	400	400	500		
	Power [W]	140	160	120		
Energy Input, E [J/mm^3]		70	80	60		
Dimensional Error, D_e [%]		+ 0.4	+ 0.5	+0.3		
Porosity, P [%]		6.1	6.2	0.2		0.4-1.1
Young Modulus, E_Y [GPa]		78	80	100	102	4-25
Yield tensile strength, $\sigma_{0.2}$ [MPa]		182	186	210	170-310	
Ultimate tensile strength, σ_{UTS} [MPa]		430	401	440	240	79-190
Roughness	R_a [μm]			3.4-4.9		
	R_z [μm]			19.1-25.3		

These tensile properties were obtained on sheet specimens manufactured with the same process parameters according to ISO 6892:2009; * ASTM F67 (Unalloyed Titanium for Surgical Implant Applications, Grade I); ** Tingart, 2003 human organism could quickly accommodate with these types of implants by reducing the weight, having the same thread form (V) and fixation would be better after the bone increases into lattice area (ingrowth osseointegration).

The yield and ultimate tensile strength of these implants presents in Table 1 are higher than values required for Surgical Implant Applications (ASTM F67), and the complex shape of these endosseous implants did not allow the measurement of roughness. Mechanical properties of Ti material obtained by SLM are two times greater than cortical bone characteristics. Despite the fact that the SLM process is capable of making full dense parts up to 97% of the materials' bulk theoretical densities little residual porosity may be still problematic for some applications where excellent strength with high ductility is necessary (Kruth, 2010).

This case study demonstrates that full dense metallic parts up to 99.8% can be generated by SLM using 60 J/mm^3 energy (Table 1, implant M_3). According to their suitable processing parameters, parts feature strength properties comparable to those of conventionally fabricated ones. Table 1 shows the influence of energy input on mechanical properties of processed Ti parts.

The Young modulus of Ti samples varied between 78-100 GPa depending on specific energy of fabrication which has been changed by tailoring the SLM processing parameters. As a result, increasing the energy input from 60 to 80 J/mm^3 was decreased the ultimate tensile strength of Ti samples from 440 to 401 MPa.

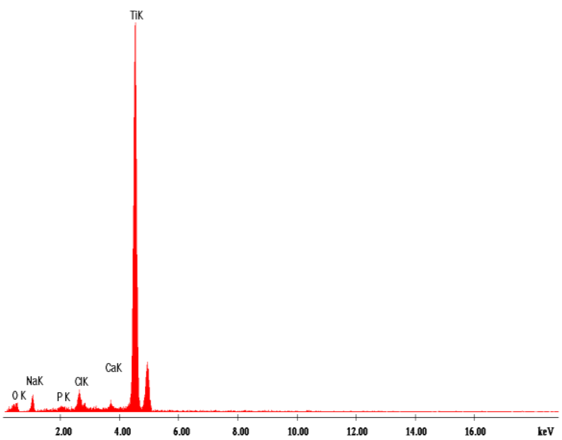
In addition, this experimental research proves that TILOP powder would be suitable manufactured by SLM with laser power between 120-160 W, respectively energy input between 60 and 80 J/mm^3. If the process conditions pass over these values the mechanical properties will decrease. Implants M_2 were fabricated with 80J/mm^3 energy and the mechanical properties were lower compared to M_1 (70 J/mm^3) and M_3 (60 J/mm^3) implants. The mechanical properties of Ti produced by SLM process are comparable to wrought annealed and are higher than cast materials. After numerous experiments, the dimensional accuracy was improved to ±0.05 mm and the error *De* was reduced to 0.3-0.5%.

Customized implants manufactured by SLM with this accuracy could be use in dentistry and the mechanical properties like tensile strength and Young's modulus can be adapted to the requirements of patient's cases using specific process parameters of SLM fabrication.

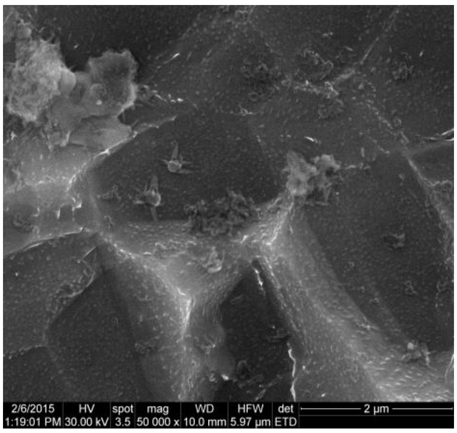
Figure 1b present screw vent implants after Reverse Torque Test (RTT). This technique is used to test the friction between the implant and the surrounding bone (Jividen, 2000). RTT is an experimental procedure in which an implant is subjected to unthreaded hole to determine the relative strength of attachment between the implant and bone. It is usually done on a comparative basis between differing implant surface topographies or roughness's (Jividen, 2000). RTT method was applied to fragments from bovine bones with 16 mm cortical bone thickness because these bones show a structure much closer to human maxillary bone structure. This test of implants has also been described as a method for determining the success of machined surfaced, threaded implants in clinical situations (Jividen, 2000). After the insertion of implants into cortical bone, all the parts were put in a hydraulic press where was exerted on implants a continuous pressure of approximately 20 N/cm^2 for about 24h and 72h. This pressure is similarly with masticatory pressure. The reverse torque was applied with a dental contra angle hand-piece and it has been tried to unscrewing the implants by applying a torque of 20 N/cm^2. Screw vent implants does not succumb at this tendency of reverse torque and show that the design has a good primary stability, even after it was applied a vertical pressure for 24h and 72h.

Knowing that the bacterial adhesion on medical implants is a main source of complications in dentistry and orthopedic surgery (Peye, 2009), (Kazemzadeh, 2010), and reports on loss of dental implants clearly define peri-implantitis as a major cause of the implant failure. Ti implants do not prevent peri-implant infections and an alternative is needed. Ti implants with bioactive coating that would have antiseptic properties could be a solution. In addition to antibiotics, antiseptics can also be immobilized to polymer coatings on orthopedic or dentistry implants (Kalicke, 2006). Chitosan (CS) is a biological, biodegradable, nontoxic polymer which has antiseptic properties and it has been shown that it can increase the growth and attachment of gingival cells (Sigla, 2001, Muzzarelli, 1999).

After SLM process, these implants were biomimetic coated in a SBF solution with 1g/l β-TCP (tricalcium phosphate) and CS. β-TCP is a ceramic mostly recruited clinically to treat bone defects or voids, it is more resorbable than hydroxyapatite and induce biomaterial replacement with new bone. Firstly, the implants were acid etching in a mix solution of 20 wt% HF and 18 wt% HNO3 for 15 sec. The implants were then exposed to ultraviolet irradiation for 12h. After soaking in SBF modified solution at 40°C for 48h, the implants were removed, washed and dried in a humid atmosphere. The pH of the SBF solution was adjusted by addition of NaOH at 6.5. Through this biomimetic process was obtained a thin film made from Ca-P/CS on implants surface. This coating technique is simple to perform respectively cost-effective, and may be applied even to heat-sensitive, non-conductive and porous materials of large dimensions and having complex surface geometries.



a)



b)

Figure 2. a) EDX spectrum of M_1 implant after biomimetic coating with β-TCP and Chitosan for 48h, b) SEM image of biomimetic coating at 50,000x magnification

The surfaces of implants were analyzed with SEM and the information about the surfaces topography and chemical composition were presented in Figure 2. Other studies with biomimetic coating of Ti in modified SBF (e.g. collagen) concluded that the osteoblastic cell proliferation was significantly higher on biomimetic samples compared to pure apatite deposit only (Xia, 2012), (Renoud, 2012). Ca/P deposition on M_1 implant surface was observed in the EDX spectrum (Figure 2). The EDX analysis has showed to be an important technique to identify biomimetic films, such as Ca/P compounds. This analysis of the deposit reveals the presence of Ti, Oxygen, Sodium, Chlorine, Calcium and Phosphorus elements. The Ca/P ratio of the deposits was also calculated as 1.56, and this novel biocoating applied on Ti can induce biomaterial replacement with new bone. It is a thin layer of Ca/P and it could show even better results if the implants were kept in SBF solution 7 days or even more according to W.S. Medeiros (Medeiros, 2008).

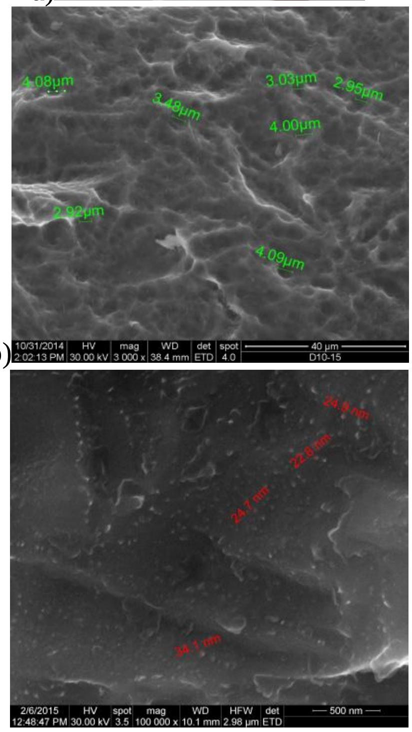
The adhesive strength between the bioactive coating and the implant is a critical parameter in determining the long-term stability of the implant. This surface treatment can be applied on implants with lattice structures and the bioactive coat will be avoiding the adhesive strength between bone and implant. Lower weight of these new implants make them more easily accepted by the human organism and the lattice structure form and micro porosity obtained with SLM process could be a solution for future infiltration or coatings with β-TCP, enzymes, growth factors or other drugs on dental implants.

3.2 Case study: Blade Implants

Blade implants can be used in any alveolar crest, but are particularly useful in the thinnest, where the use of root-form implants is difficult and needs bone regeneration procedures. The advantages of blade implants are as follows: possibility to insert in the alveolar crests, adaptability to the majority of anatomical conformations, avoiding bone regeneration surgery, mechanical correction of parallelism during implant surgery, adaptation to the deep anatomical structures by modifying the implant, presence of numerous contacts with cortical layer, possibility of inserting a part of the implant below the intact cortex and simple surgical technique performed with standard instruments (Dal Carlo, 2013). Blade implants bodies are inserted between the superficial cortical bone and the superior side of the alveolar canal. A complex retrospective study on 522 implants was developed and it shows that the success rate of blade implants was 98% at 5 years, 89% at 8 years and 86% at 10 years (Dal Carlo, 2013). In conclusion, the blade implant is a valid therapeutic device useful for treating cases such as narrow bone crest and scarce spongy bone in the lower distal sector and they have demonstrated long-term survival.

Knowing the benefits of blade endosseous implants, it was designed and manufactured a novel model (M_3), and the aim was to obtain by SLM these implants with specific roughness and accuracy followed by a bioactive coating (Figure 3).

a)



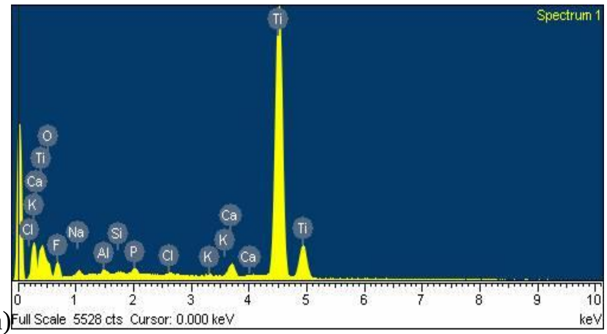
b)

Figure 3. a) Blade implants M_3, b) SEM image of M_3 implant surface after acid etching and abrasive blasting, 3000x and 100,000x magnification

It was fabricated 10 pieces with different values for outer boundary process parameter and the surface roughness acquired is presented in Table 1. The values for R_a were between 3.4 - 4.9 μm and were afforded without any post-process treatment. The R_a respectively R_z are lower compared with other studies in AM technology, where was obtained for R_a values between 5 to 20 μm (Gebhardt, 2014), (Vijay-Arasu, 2014), (Campanelli, 2013), (Kruth, 2008). By suitable outer bondary process parameter, the roughness R_a was 3.4 μm and it was avoided additional pre-finishing operations. The roughness established in this research represents a micro- porous zone perfect to proliferation of osteoblast cells and osseointegration. An in vitro and in vivo research was carried out about how the roughness influences the osseointegration (Herrero-Climent, 2013). This research demonstrated that the roughness and topographical features are the most relevant of the surface properties for a dental implant or its biological response. The surfaces with increasing roughness show more osteoblastic adhered cells. This effect was most pronounced on samples with Ra around 4μm and these samples don't have any failure because this roughness gives a primary stability to implants (Herrero-Climent, 2013).

The histomorphometric quantification of the osseointegration of the implants demonstrates that highly rough surfaces improve bone integration compared to those as-machined with R_a = 0.7 μm or acid-etching with R_a = 1.5 μm (Herrero-Climent, 2013). These results were confirmed by the *in vivo* test, where after 10 weeks the ossteointegration was around 49% for implants with R_a = 4 μm and 26% for those with lower roughness (Herrero-Climent, 2013). This research and others (Wennerberg, 2000) concluded that the surface rough influence the bone behavior and blade implants as those developed with R_a between 3.4-4.9 μm can be a solution for better osseointegration.

To improve the surface of M_3 implants, they were acid etching and abrasive blasting in order to provide both a micro-roughness and waviness that seems to enhance bone contact with the implant surface (Figure 3b). The Ti surface was first acid etching in a mix solution of 20 wt% HF and 25 wt% HNO_3 for 10 sec. to forming a micro-rough surface, followed by grit-blasted with large particles of abrasive apatite (MCD 180) creating a grossly rough surface. Accompanied with acid-etching, MCD particles with diameter between 150-200 μm have easily prepare Ti surface with suitable multi-level structure morphology (1-4 μm micro pits, Figure 3b) and moderate roughness for osseointegration. Note that the surface mainly displays a honeycomb-like structure. Figure 3b illustrates that a thin and uniform coating of Ca/P material has been blasted onto the surface and successfully deposited as a stable layer onto the Ti surface and it can see at 100,000x magnification nanoparticles of apatite with diameter between 22-34 nm.

a)


Element	O	F	Si	P	Cl	Ca	Ti
Weight [%]	7.9	11.8	0.2	0.5	0.2	1.9	75.4

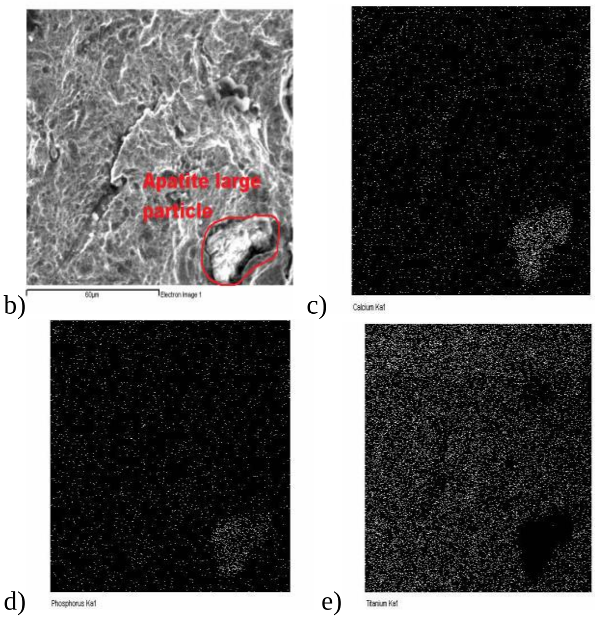


Figure 4. a) EDS spectrum and chemical composition of M_3 implant after acid etching and abrasive blasting b) SEM image with large apatite particle on M_3 implant surface (1000x magnification), and elemental maps with spatial distribution of c) Ca, d) P and e) Ti

After this treatment chemical composition obtained is presented in EDS spectrum (Figure 4), where the Ca/P ratio of the deposits was calculated as 3.47 and this high ratio can be explained by the fact that these rough surfaces have mechanical deposits of large apatite particles (diameter between 10-30 μm). Through elemental maps with spatial distribution of Calcium and Phosphorus (Figure 4b) was prove the presents of large apatite particles mechanically anchored in the porous surface. The final roughness R_a results after this surface treatment process was around 3.3 μm and this roughness is compatible with the dimensions of new-formed osseous cells, and let them to grow inside pores, differentiate and anchor to the implant surface (Wennerberg, 2000). The study proves the sustainability of SLM process in manufacturing of dental implants and the possibility to develop a new branch of the customized dental implants. Traditional implants have their limitation and they are not better fit due to the difference of patient's oral condition (Chen, 2012).

4 CONCLUSIONS

This research was demonstrated that proper process conditions for SLM manufacturing of customized parts with a predefined surface roughness and morphological characteristics could be defined. It's obvious that process conditions of fabrication direct influence the mechanical properties and was proved how it can be manufactured customized implants from pure Ti powder using suitable process parameters. The mechanical characteristics obtained have higher values for yield and ultimate strength compared to standard typically required of Unalloyed Titanium for Surgical Implant Applications, and it is also two times greater than cortical bone.

It was designed and manufactured by SLM novel customized parts like: screw vents and blade implants for dentistry. All these applications have the dimensional accuracy down to 50 μm and it can be achieved considering the particle diameter of powder and the proper set up of the outer boundary process parameter. Through SLM technology, geometry and surface retention related limitations set by traditionally molded or milled suprastructures no longer apply.

To avoid complex post-processing techniques, it was fabricated implants with adequate process conditions and the roughness results (R_a) was down to 4 μm, moreover after specific pre-finish process roughness decreased at 1 μm. Moderate roughness, suitable topography and specific coatings can encourage the osteoblast cells to adhere, proliferate and differentiate on Ti comparison with the smooth one. On these dental implants were applied two different surface treatments like biomimetic coating in modified SBF solution with biodegradable β-TCP and CS, respectively acid etching in HF and HNO_3 followed by grit-blasted with abrasive apatite powder. Afterwards the surfaces were analyzed with SEM microscopy and EDX spectrum. Further *in vitro* and *in vivo* tests are needed on implants made by SLM and bioactive coated with these methods which modified the surface composition. These studies are necessary to see if the surface treatments described can contribute to a better proliferation of cells and increase the osseointegration process.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

►Kruth, J.-P., Vandenbroucke, B., Van Vaerenbergh , J., Naert, I. (2005). *Digital Manufacturing of biocompatible metal frameworks for complex dental prostheses by means of SLS/SLM*, Proc. of 2nd Int. Conf. on Advanced Research in Virtual and Rapid Prototyping, Leiria, pp. 139-145, Sept. 2005.

►Berce, P., Chezan, H., Balc, N.(2005). *The application of Rapid Prototyping Technologies for manufacturing the custom implants*, 8th ESAFORM Conference on Material Forming, Cluj-Napoca, pp. 27-29, April 2005.

►Leordean, D., Dudescu, C., Marcu, T., Berce, P., Balc, N. (2015). *Customized implants with specific properties, made by selective laser melting*, Rapid Prototyping Journal, 21(2), 2015.

►Biemond, J.E., Hannink, G., Verdonschot, N. , Buma, P. (2013), Bone ingrowth potential of electron beam and selective laser melting produced trabecular-like implant surfaces with and without a biomimetic coating, J. Mater Sci. Mater Med. 24(3):745-53.

►Palanuwech, M. (2003). The fatigue resistance of commercially pure titanium (grade II), titanium alloy (Ti6Al7Nb) and conventional cobalt-chromium cast clasps, PhD Thesis, University of Tübingen, 2003.

►Bandyopadhyay, A., Espana, F., Balla, V. , Bose, S., Ohgami, Y., Davies, N. (2010). *Influence of Porosity on Mechanical Properties and In vivo Response of Ti6Al4V Implants*, Acta Biomater, 6(4): 1640–1648.

►Liu, X.Y., Chu, P., Ding, C.X. (2004). Surface modification of titanium, titanium alloys, and related materials for biomedical applications, Mater. Sci. Eng. R. Rep. 47:49–121.

►Pyka, G., Kerckhofs, G., Papantoniou, I., Speirs, M., Schrooten, J., Wevers, M. (2013), *Surface Roughness and Morphology Customization of Additive Manufactured Open Porous Ti6Al4V Structures*, Materials, 6:4737-4757.

►Muresan, S., Balc, N., Pop, D., Fodorean, I. (2011). *Influence of Process Parameters To Manufacture Titanium Parts By SLM*, The 10-th International MTeM Conference Proceedings, Cluj-Napoca, pp. 210-213, October 2011.

►Muresan, S. (2011). Research on mechanical properties of complex parts manufactured by selective laser melting, PhD Thesis, Technical University of Cluj-Napoca.

►Lerodean, D. (2011). Theoretical and experimental research of Rapid Prototyping technologies for customized orthopedic implants, PhD Thesis, Technical University of Cluj-Napoca.

►Misch, C.E., Bidez, M.W. (1999). *A scientific rationale for dental implant design*, In: Misch CE, Contemporary Implant Dentistry, St. Louis: Mosby.

►Branemark, P.I. (1983). *Osseointegration and its experimental background*, J. Prosthet. Dent., 50:399-410.

►Collins, M., Bassett, J., Wen, H., Gervais, C., Lomicka, M., Papanicolaou, S. (2012). *Trabecular Metal Dental Implants: Overview of design and developmental research*, Zimmer Dental Study.

►Chen, X., Xie, L., Chen, J., Du, R., Deng, F. (2012). *Design and fabrication of custom-made dental implants*, J. Mech. Sci. Technol., 26:1-6.

►Figliuzzi, M., Mangano, F., Mangano, C. (2012). *A novel root analogue dental implant using CT scan and CAD/CAM: selective laser melting technology*, Int. J. Oral Maxillofac. Surg., 41: 858-62.

►Cosma, S. C., Balc, N., Leordean, D., Matei, S. (2014). *Dental implants with lattice structure fabricated by Selective Laser Melting*, International Virtual Research Conference in Technical Disciplines, Slovakia.

►Jividen, G., Misch, C.E. (2000). *Reverse torque testing and early loading failures: help or hindrance?*, J. Oral Implantol., 26(2):82-90.

►Esen, Z., Bor, S. (2007). Processing of titanium foams using magnesium spacer particles, Scripta Materialia, 56, 341-344.

►Lu, J.X., Flautre, B., Anselme, K., Hardouin, P., Gallur, A. (1999). Descamps, M., *Role of interconnections in porous bioceramics on bone recolonization in vitro and in vivo*, Journal of Materials Science: Materials in Medicine, 10:111-120.

►Kruth, J.-P., Badrossamay, M., Yasa, E., Deckers, J., Thijs, L., Van Humbeeck, J. (2010). *Part and material properties in selective laser melting of metals*, 16th International Symposium on Electromachining, Shanghai, China.

►Peye, A.D., Lockhart, D.E., Dawson, M.P., Murray, C.A., Smith, A.J. (2009). *A review of* *dental implants and infection*, J. Hosp. Infect., 72(2): 104–110.

►Kazemzadeh, M., Duan, K., Jenssen, H.,. Hancock, R. E, Wang, R. (2010). *Antimicrobial peptides on calcium phosphate-coated titanium for the prevention of implant-associated infections*, Biomaterials, 31(36): 9519–9526.

►Kalicke, T., Schierholz, J., Schlegel, U., Frangen, T.M., Koller, M., Printzen, G., Seybold, D., Klockner, S. (2006). Effect on infection resistance of a local antiseptic and antibiotic coating on osteosynthesis implants: An in vitro and in vivo study, J. Orthop. Res., 24:1622–1640.

►Singla, A.K., Chawla, M. (2001). *Chitosan: some pharmaceutical and biological aspects – an update*, J. Pharm. Pharmacol, 53(8): 1047–1067.

►Muzzarelli, R.A., Mattioli-Belmonte, M., Pugnaloni, A. (1999). *Biochemistry, histology and clinical uses of chitins and chitosans in wound healing*, EXS, 87: 251–264.

►Renoud, P., Toury, B., Benayoun, S., Attik, G., Grosgogeat, B. (2012). Functionalization of Titanium with Chitosan via Silanation: Evaluation of Biological and Mechanical Performances, PLoS One, 7(7): e39.

►Xia, Z., Yu, X., Wei, M. (2012). *Biomimetic collagen/apatite coating formation on Ti6Al4V substrates*, J. Biomed. Mater. Res., 100(B):871-881.

►Medeiros, W.S., Oliveira, M., Pereira, C., Andrade, M.C. (2008). *Bioactive Porous Titanium: An Alternative to Surgical Implants*, Artif. Organs., 32(4):277-82.

►Dal Carlo, L., Pasqualini, M.E., Carinci, F., Corradini, M., Vannini, F., Nardone, M. (2013). *A brief history and guidelines of blade implant technique: a retrospective study on 522 implants*, Annals of Oral & Maxillofacial Surgery, 1(1):3.

►Gebhardt, A., Hötter, J., Ziebura, D. (2014), *Impact of SLM build parameters on the surface quality*, RTejournal - Forum für Rapid Technologie.

►Vijay-Arasu, I., Chockalingam, K., Kailasanathan, C., Sivabharathy, M. (2014). *Optimization of Surface Roughness in Selective Laser Sintered Stainless Steel Parts*, International Journal of ChemTech Research, 6(5):2993-2999.

►Campanelli, S.L., Casalino, G., Contuzzi, N. (2013). Taguchi Optimization of the Surface Finish Obtained by Laser Ablation on Selective Laser Molten Steel Parts, Procedia CIRP, 12: 462–467.

►Kruth, J.-P., Yasa, E., Deckers, J. (2008). *Roughness improvement in selective laser melting*, Proceedings of the 3rd International Conference on Polymers and Moulds Innovations.

►Herrero-Climent, M., Lázaro, P., Vicente Rios, J., Lluch, S., Marqués, M., Guillem-Martí, J., Gil, F. J. (2013). *Influence of acid-etching after grit-blasted on osseointegration of titanium dental implants: in vitro and in vivo studies*, J. Mater Sci: Mater Med, 24:2047-2055.

►Wennerberg, A., Albrektsson, T. (2000). *Suggested Guidelines for the Topographic Evaluation of implant surfaces*, Int. J. Oral Maxillofac, Implants 15: 331-344.

►Chen, X., Xie, L., Chen, J., Du, R., Deng, F. (2012). *Design and fabrication of custom-made dental implants*, Journal of Mechanical Science and Technology 26 (7).

►Tingart, M. J., Apreleva, M., Von Stechow, D., Zurakowski, D. J. (2003). *The cortical thickness of the proximal humeral diaphysis predicts bone mineral density of the proximal humerus*, J. Bone Joint Surg. Br, 85(B):611-61.

7 NOTATIONS

The following symbols are used in this paper:

AM - Additive Manufacturing

Ca/P – Calcium/Phosphorus

CS - Chitosan

EDX/EDS - Energy-Dispersive X-ray Spectroscopy

HF - Hydrofluoric acid

HNO_3 - Nitric acid

MCD – Apatite abrasive

M_1, M_2, M_3 - Dental implants manufactured with different process conditions

R_a - Roughness parameter

RTT - Reverse Torque Test

SBF – Simulated Body Fluid

SEM - Scanning Electron Microscopy

SLM - Selective Laser Melting

Ti - Titanium

β-TCP - Tricalcium phosphate