

# EVALUATION OF THE SPACE HOLDER TECHNIQUE FOR PROCESSING OF POROUS TITANIUM AS BIOMATERIAL

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**Abstract**— The objective of this paper is the manufacture of a porous metal structure from commercially pure titanium powder grade 1, aiming at the possible application as a biomaterial in the regeneration of bone tissues assuming its architecture. Experimental methods were used to evaluate the effectiveness of the use of the space holder technique in the manufacture of powder metallurgy (MP). In the samples produced, 50% by volume of titanium powder and 50% of chemical reagent (Sodium Chloride - NaCl and Ammonium Bicarbonate -  $\text{NH}_4\text{HCO}_3$ ) were added, compressed with a pressure of 250 Mpa. The metal-only test samples were compacted with pressures of 70 MPa and 250 MPa. The architecture found with the use of space holder was satisfactory, presenting sufficient conditions of size, morphology, and interconnectivity for bone growth within the structure. Samples made only with metal powder do not have enough pores even with lower compaction pressure.

**Keywords**— Powder Metallurgy; Space Holder; Biomaterials; Porous Structure; Titanium; Medical Implants; Osseointegration; Porosity.

## I. INTRODUCTION

The increase in the expectation and quality of life have driven technological advances in the health area, developed techniques that seek to reestablish and correct functions of the human body affected by diseases, accidents, aging and other causes (Liu *et al.*, 2004; Rodrigues, 2013; Souza *et al.*, 2012). Synthetic biomaterials such as metals, more specifically titanium and its alloys are used in biomedical components and devices. They are used in substitutions and reconstitutions of hard tissues, as well as cardiovascular applications because they present excellent biocompatibility, biofunctionality, resistance to fatigue, resistance to corrosion and relatively low modulus of elasticity compared to other metals. However, there are still problems to be solved as the difference between the elasticity modulus of the solid metallic material and the bone, which can lead to failures and shorten the lifespan of the human being, depend on the type and quality of the interface originated (Goia, 2013). The development of biomaterials with porous structures have been used as support in the regeneration of hard tissues, this kind of structures

has been studies since the sixty decade to produce a stronger interface for clinical applications, which in turn imitate their architecture, improving biological, chemical and mechanical properties. With bone growth inside the pores it act like a dynamic composite material, making it difficult to bone resorption at the interface with the implant, allowing migration and proliferation of cells, blood irrigation and modulus of elasticity reduction (Dunand, 2004; Goia, 2013; Liu *et al.*, 2004; Nilles *et al.*, 1973; Nouri *et al.*, 2010). One method of obtaining porous implants is the process of manufacturing through powder metallurgy (Espinoza *et al.*, 2005), which generates a porous and rough surface, also providing an increase in the area of contact between bone and implant, it is resulting in better interlocking. Most of the manufactured implants are derived from processes such as precision casting, rapid proto-typing and machining. The manufacturing sequence and the types of processes selected will depend on several factors, such as: geometry, properties (physico-chemical and mechanical) and the costs associated with each component (Rocha, 2010).

Many biomaterials implanted in humans are used to alleviate certain clinical conditions, improve quality of life and increase survival time. The term "biomaterial" is defined as a possible material to be in contact with biological organisms and is intended to treat, diagnose, increase or replace any tissue, organ or function in living beings (Ratner *et al.*, 1996).

Metallic materials, because of their good mechanical properties, are the main materials used in implant manufacturing, among them the stainless steel 316L (ASTM F138, 2013), Co-Cr-Mo alloys (ASTM F75, 2012) and (ASTM F567) Co-Ni-Cr-Mo (ASTM F562, 2013) titanium (Grade 1, 2, 3 and 4, ASTM F67, 2006) and Ti-6Al-4V (ASTM F136, 2011). For the application to orthopedics, there are examples of use in articulated prostheses and structural parts in the fixation of osteosynthesis fractures (Oréfice *et al.*, 2006). There are several implants and prosthesis used in humans (Fig 1).

Titanium and its alloys are used in industrial applications (aerospace, nano-aerospace, heat exchangers, chemical, naval, nuclear and military), medical, among others. Some reasons that lead to its use in several areas are low density, excellent corrosion resistance, good mechanical properties and non-magnetic characteristics (Braga and

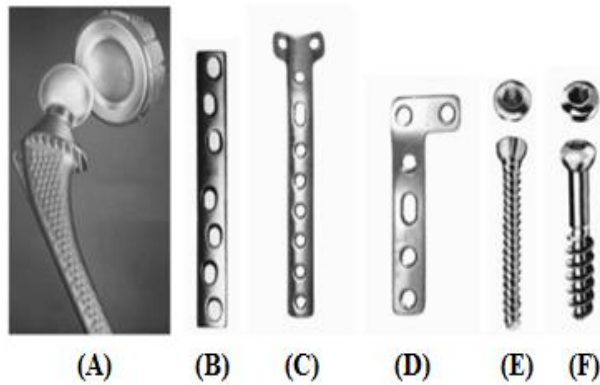


Fig. 1. (A) Hip prosthesis; (B) Compression plate for osteosynthesis; (C) T-compression plate; (D) L-shaped compression plate; (E) Screw for cortical bone; (F) Screw for spongy bone (Oréface *et al.*, 2006).

Ferreira, 2007; Oréface *et al.*, 2006; Cozza *et al.*, 2018).

There is a need for corrosion resistance for implants because of the extracellular body fluids have sufficient concentration of ions capable of causing oxidation of metallic materials, in addition to containing amino acids and proteins that tend to accelerate the process mentioned above. Corrosion tends to release metallic particles into body fluids, which over a prolonged period of exposure can cause toxicity in the body (Liu *et al.*, 2004).

The requirements for a material to come into contact with living tissue go beyond corrosion resistance must be biofunctional and biocompatible. The biocompatibility is related to restoring the function of the hard tissue and biocompatibility is a characteristic so that the material is suitable for the body, not involving inflammatory or allergic reactions (Goia, 2013).

Finally, osteoconductivity is determined by the property of certain materials to support bone growth on its surface (Fujibayashi *et al.*, 2004).

The healing of the implant at the interface with the bone goes through the same steps as a direct fracture, that is, an inflammatory process begins, where living tissue reacts to any type of aggression. The physical and chemical properties of the biomaterials, the topography and shape of the implant at the interface with the tissue, are factors influencing the intensity and time of inflammation, exemplifying, more inert materials that interact properly with connective tissues may provide a minimum level of inflammation, accelerating the healing process (Oréface *et al.*, 2006).

After the inflammation occurs the initial stabilization, healing begins with the formation of a clot and blood vessels. The osteoprogenitor cells multiply in the medium differentiating in osteoblasts, occurring the deposition of bone in the implant (Spencer, 1991).

At the interface between the implant (almost or inert) and the bone when osseointegration does not occur, a thin fibrous capsule will be formed separating the dense tissue from the biomaterial, with little or no adhesion between the parts (Oréface *et al.*, 2006).

Table 1. Comparison of the mechanical properties of the sample Ti, Ti-6Al-4V and the bone tissue (cortical and spongy) (Ratner *et al.*, 1996; ASTM F67, 2006; ASTM F136, 2011).

Name of material/bone	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Rupture Strength (MPa)
Sample Ti – grade 1	105	138 - 221	240 - 345
Ti-6Al-4V – grade 23	110	759 - 828	828 - 910
Cortical bone	15 - 30	30 - 70	70 - 150
Spongy bone	0.05 - 0.5	-	-

When dealing with pure titanium grade 1, it will be the metallic material applied in the experiments of this paper, mechanical properties (Table 1) as per the specification of the standard (ASTM F67, 2006). For comparison, the same table presents the Ti-6Al-4V titanium alloy data in accordance with ASTM F136 (2011), in addition to the properties of cortical and spongy bone (Ratner *et al.*, 1996).

Pure titanium has a modulus of elasticity of 105 GPa (Table 1), the value is much higher than that found in bones that are from 10 GPa to 30 GPa, this difference in stiffness can lead to bone resorption, stress concentration and, eventually, implant release (Cremasco, 2012; Liu *et al.*, 2004; Nilles *et al.*, 1973; Oh *et al.*, 2003).

Porous implants require specific pore size and morphology for their good functionality, among the used methods for this, the technique via space holder is considered the simplest to be applied. This approach can provide high levels of porosity and better control over them (Bomfim, 2014; Oréface *et al.*, 2006). Such a procedure consists of mixing the metal powder with space holder, compacting and subjecting the green compacted to a sintering treatment to eliminate the sparing agent.

The decomposition of the space holder through the heat treatment leaves empty spaces, revealing a porous structure. However, the pores produced may be excessively large, and the technique occasionally leaves impurities in the material (Bomfim, 2014). The structure can be analyzed before and after the heat treatment of removal of the space holder (Fig. 2).

The average percentage addition of space holder to pore formation is in the range of 50% to 85% by volume. These values are sufficient to form an interconnected structure and easy to remove through heat treatment. The percentage use of less than 50% by volume will cause imprisonment in the structure and above 85% will lead to extreme fragility of the component (Torres *et al.*, 2014).

When analyzing the powder metallurgy manufacturing process, with the use of space holder the size of the scattering agent should be greater than 100  $\mu\text{m}$  since the space left by them should provide bone growth and vascularization when installing in a patient (Arifvianto and Zhou, 2014). Pore size is a very important factor, when Herman *et al.* (1975) fabricated carbon prosthesis with porous diameter less than 20  $\mu\text{m}$  size they do not found satisfactory

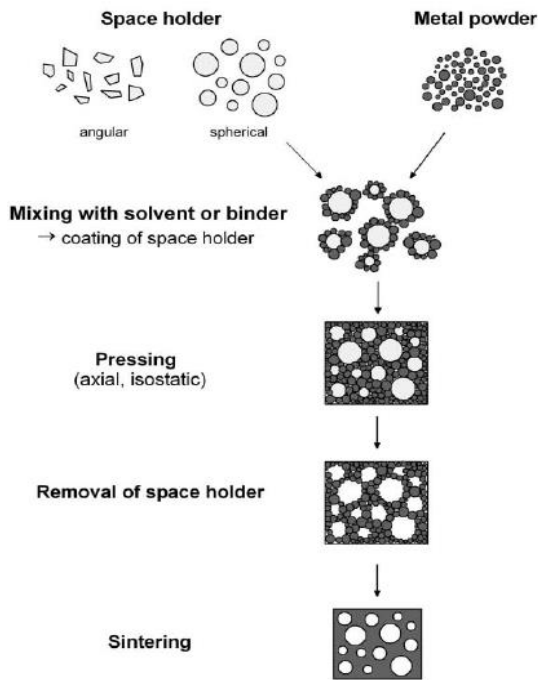


Fig. 2. Structure before and after space holder removal heat treatment (Banhart, 2001).

bone growth, in another hand pore size 200 and 300  $\mu\text{m}$  gave adequate results. For example, to achieve a pore size 300  $\mu\text{m}$  - 400  $\mu\text{m}$ , it is ideal to use space holder ranging from 100  $\mu\text{m}$  - 500  $\mu\text{m}$  (Quian and Guo, 2015).

This technique is considered a modern method to obtain porosity and homogeneity when manufactured structures via powder metallurgy (Arifvianto and Zhou, 2014).

Titanium and its alloys, when implanted in a human with a massive structure, do not respond well to cyclical situations due to the difference in the modulus of elasticity between the bone and the implant, with a shielding voltage due to this inequality. Producing porous implants via powder metallurgy have been employed to reduce the modulus of elasticity and provide a better fixation interface through the bone growth in the interior, forming a structural and functional bond known as osseointegration (Nouri *et al.*, 2010; Braga and Ferreira, 2007; Oréfice *et al.*, 2006; Kujala *et al.*, 2003). This type of mechanical coupling inhibits the formation of a fibrous capsule, making movement between the parts difficult (Oréfice *et al.*, 2006).

Porous implants should allow tissue invasion through interconnected pores, facilitating vascular maintenance (transport of oxygen and nutrients), host cellular and extracellular components, thereby providing a continuous mineralization of bone tissue (Niinomi, 2003; Murphy *et al.*, 2010; Hedayati *et al.*, 2016; Oréfice *et al.*, 2006). The pores in implants can also serve for the deposition of drugs that stimulate bone regeneration and vascularization, preventing infections (Vasconcellos *et al.*, 2012).

When fabricating solid and porous implants (using urea as space holder) and performing in vivo experiments, researchers noted results of the osseointegration of both types of samples after the four-week recovery time (Vasconcellos *et al.*, 2012).

Table 2. Percentage of powders for each type of sample.

Space holder	% of volume
Sodium chloride	50% titanium powder and 50% sodium chloride
Ammonium bicarbonate	50% titanium powder and 50% ammonium bicarbonate
-	100% titanium powder

## II. METHODS

For this paper the pure titanium powder was used, the particle diameter being between -230 and + 325 mesh.

Two high purity chemical reagents selected as space holder, sodium chloride and ammonium bicarbonate were used. According to the literature (Quian and Guo, 2015) to form a pore size structure implant between 300  $\mu\text{m}$  - 400  $\mu\text{m}$ , it is ideal to use space holder ranging from 100  $\mu\text{m}$  - 500  $\mu\text{m}$ . For the samples that received an addition of space holder, 50% - 50% by volume used for the titanium powder and the reagent. The other samples will use only the titanium powder for the manufacture of porous structures to compare the resulting porosity with and without the use of the space holder technique. In Table 2 summarizes the percentages of powders for each sample type. All the samples are of pure titanium or titanium and sparing agent had a weight of 10 grams.

As the purpose of the use of the space holder technique is to provide high levels of porosity with a good control over pore size and morphology. The compaction of samples without the addition of scattering agents served to verify the effectiveness of this methodology.

A pure titanium sample compacted with a pressure of 70 MPa, where it is expected to find a certain degree of porosity after the end of the sintering process.

Three another samples packed with 250 MPa pressure, pure titanium, titanium plus sodium chloride and titanium plus ammonium bicarbonate.

For sintering, the available equipment is the electric resistive furnace with a maximum temperature of 1200°C, to avoid the chemical reactivity of titanium with nitrogen and oxygen, a controlled atmosphere of argon used under conditions of positive pressure throughout the time of the samples remaining in the furnace.

Two tests were performed after the granulometric adjustment of the chemical reagents, particle characterization of the materials, mixing of powders, compaction, removal of space holder and sintering. To verify if the parameters listed and the conditions for the existing production would yield satisfactory results, the first test (Table 3) the samples would be the most prone to disintegration due to the low compression. The first two samples  $S_1$  and  $S_2$  were maintained throughout the sintering and cooling time inside the furnace, with an inert atmosphere at positive pressure without constant gas flow.

After analyzing the results of Sample  $S_1$  and Sample  $S_2$ , a second test was carried out, differentiating from the first the sintering temperature, the sample inerting and cooling method. The inert gas remained at constant flow throughout the process and, after two hours of sintering. The sample  $S_3$  cooled in water and the sample  $S_4$  cooled in air (Table 3), the result was not satisfactory and demon-

Table 3. Development of samples.

Samples	Material	Compact (MPa)	Sintering
S <sub>1</sub>	Titanium	70	1000 °C - 2 hours
S <sub>2</sub>	Titanium 50% NaCl 50%	250	1000 °C - 2 hours
S <sub>3</sub>	Titanium	70	1100 °C - 2 hours
S <sub>4</sub>	Titanium	250	1100 °C - 2 hours
S <sub>5</sub>	Titanium	70	1100 °C - 2 hours
S <sub>6</sub>	Titanium	250	1100 °C - 2 hours
S <sub>7</sub>	Titanium 50 % NaCl 50%	250	1100 °C - 2 hours
S <sub>8</sub>	Titanium 50 % NH <sub>5</sub> CO <sub>3</sub> 50%	250	1100 °C - 2 hours

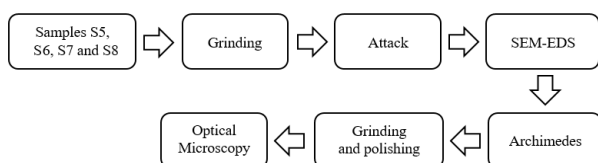


Fig. 3. The procedure used for sample evaluation.

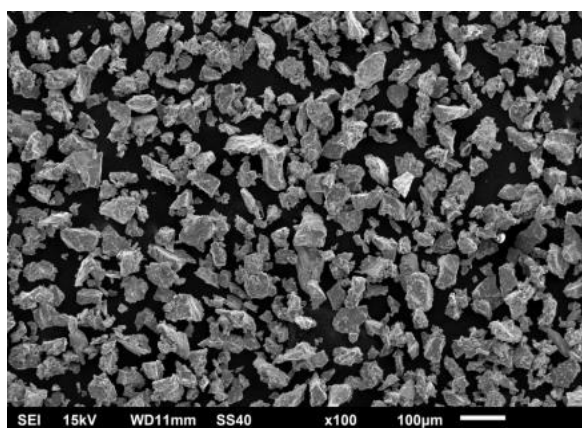


Fig. 4. SEM of titanium metallic powder.

strate strong superficial oxidation, the next samples were maintained inside the furnace to cooling with positive pressure and constant gas flow.

SEM and EDS analyzed the metal powder and the reagents, the particulate sizes were calculated using ImageJ software and their morphologies classified according to the literature, besides the qualitative identification of the chemical elements. After sample preparation, the evaluation procedure follows the flowchart steps (Fig. 3).

The granulometric distribution of the metallic powder, based on the measurement of sample data (30 particles), presents an average size of 51 µm and angular morphology (Fig. 4).

Because the reagents sieved in macro-size, a few of these are visible (Fig. 5) (sodium chloride) there are particles of the expected size (between 100 µm and 500 µm) with cubic morphology.

For the ammonium bicarbonate, there are similar particle sizes, differing in morphology that is predominantly angular and existence of acicular forms (Fig. 6).

An evaluation by EDS qualitatively provides the chemical elements present in the metal powder and the reagents. The following is the spectroscopy performed on each element (Figs. 7-9).

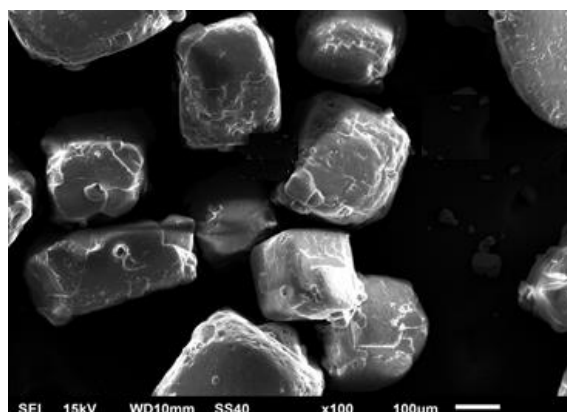


Fig. 5. SEM of the sodium chloride.

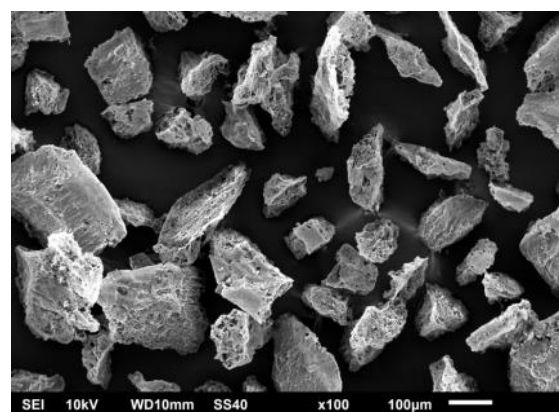


Fig. 6. SEM of the ammonium bicarbonate.

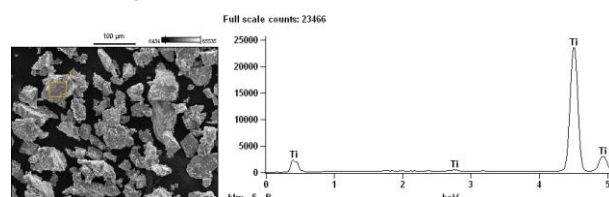


Fig. 7. EDS of the titanium powder.

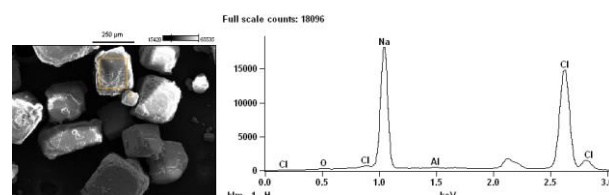


Fig. 8. EDS of the sodium chloride.

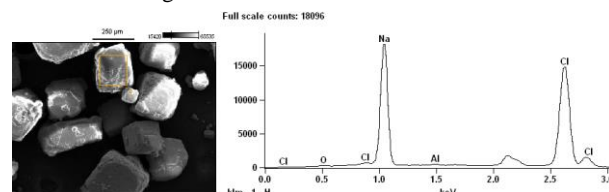
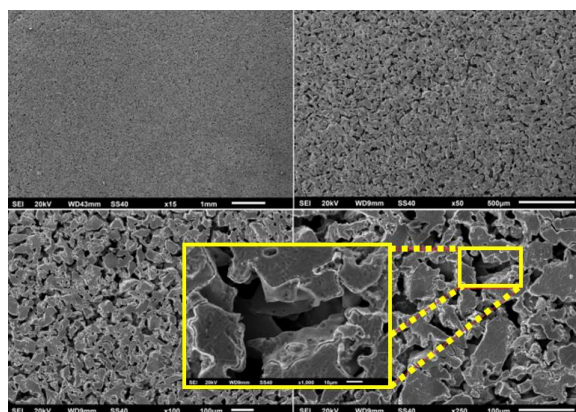
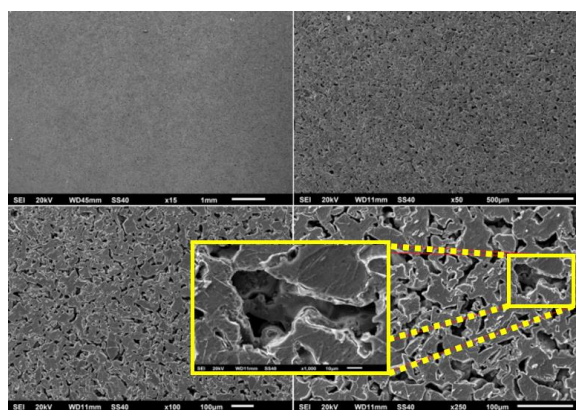


Fig. 9. EDS of the ammonium bicarbonate.

The EDS analysis (Fig. 7) did not verify the presence of other elements than titanium. As for sodium chloride and ammonium bicarbonate (Fig. 8-9), items such as aluminum (sodium chloride and ammonium bicarbonate) and silicon (ammonium bicarbonate) are not common reagent constituents. These can come from sieving (sieves manufactured from aluminum) and from residues left by previous experiments.

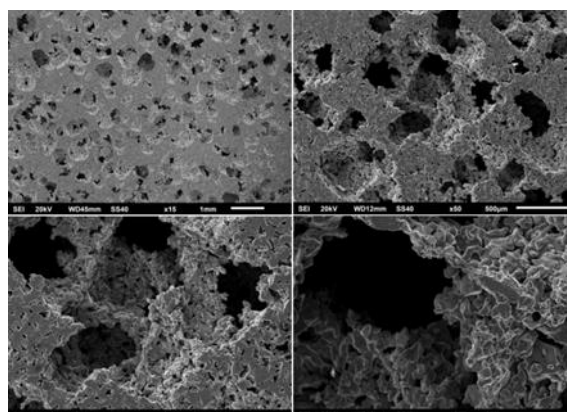
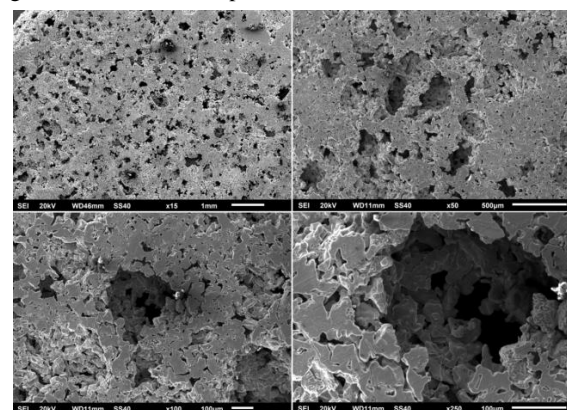
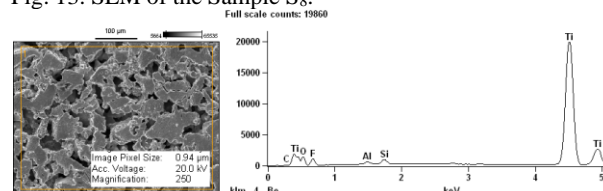


Fig. 10. SEM of the Sample S<sub>5</sub>.Fig. 11. SEM of the Sample S<sub>6</sub>.

Two tests were performed to verify the parameters initially proposed, and the existing equipment would yield satisfactory results. In the test one, the analysis of the procedure revealed coherence with the literature regarding parameters and also care to be taken. When compacted at 70 MPa pressure, Sample S<sub>1</sub> proved to be very brittle by quickly crushing during handling, Sample S<sub>2</sub> did not show good homogeneity in mixing the metal powder with sodium chloride for one hour in the mixer. During the processing of the piece to remove the space holder in water, there was a collapse of part of the structure, also as in peripheral regions with higher salt concentration due to lack of homogeneity. However, the biggest problem in test 1 was the absence of inerting the furnace.

Based on the results, a new test was developed (Fig. 10) with the objective of making samples with no oxidation, for which a constant flow of inert gas in the furnace during sintering was applied. Cooling after sintering of Sample S<sub>3</sub> (in water) resulted in sample rupture, and generalized oxidation and cooling of Sample S<sub>4</sub> resulted in shrinkage about the dimensions of the green compacted and roughened 0.6 mm, keeping the core preserved.

To achieve a better homogeneity in the mixing of the metal powder with space holder the residence time in the stirrer for 1 h 30 min (Sample S<sub>7</sub> and Sample S<sub>8</sub>) was increased. Better uniformity of particle distribution reduced the oxidized layer of the samples to approximately 0.3 mm. Shrinkage of the sintered product occurred, and the oxidized layer was removed, and only the core was analyzed, so the inert atmosphere during the stay of the pieces in the oven was not achieved.

Fig. 12. SEM of the Sample S<sub>7</sub>.Fig. 13. SEM of the Sample S<sub>8</sub>.Fig. 14. Sample S<sub>5</sub>, EDS.

Images generated by SEM can compare the technique with and without use of space holder for the fabrication of porous architectures in the metallic material of the bodies of tests Sample S<sub>5</sub>, Sample S<sub>6</sub>, Sample S<sub>7</sub> and Sample S<sub>8</sub> obtained by SEM (Figs. 10-12).

Sample S<sub>5</sub> and S<sub>6</sub> exhibit irregular pores, whereas samples S<sub>7</sub> and S<sub>8</sub> were quite promising to bone growth according to the literature. The samples confirmed the existence of interconnected macro and micropores that favor the maintenance and nutrition of bone cells and that the S<sub>7</sub> presents pore closer to the spherical shape.

In the conditions of the volumetric proportion of powder, space holder, compaction pressure and sintering temperature, there is also the presence of isolated macro and micropores.

An evaluation by EDS can qualitatively provide the chemical elements present in the samples, thus knowing if there is contamination by other constituents (Figs. 14-17) through spectroscopy performed in each sample.

Fluorine, aluminum and silicon are the chemical elements present on the delimited surface of the samples for analysis that are not part of the constituent specifications of grade 1 pure titanium as designated by ASTM F67

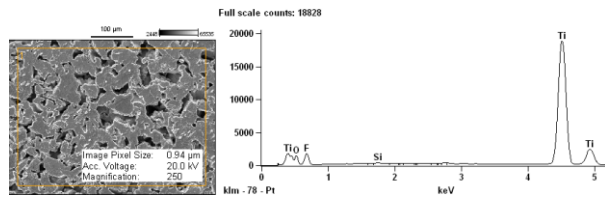


Fig. 15. Sample S6, EDS.

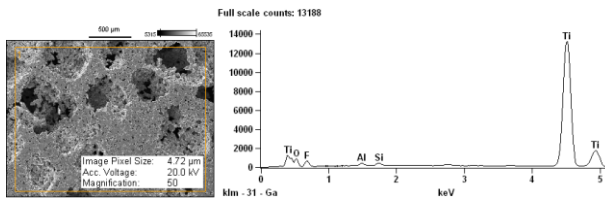


Fig. 16. Sample S7, EDS.

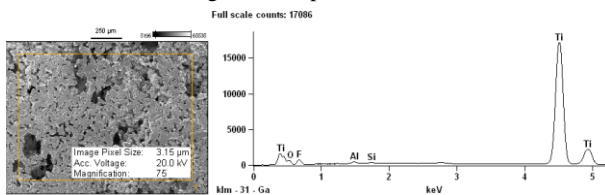


Fig. 17. Sample S8, EDS.

Table 4. Apparent porosity connected to surface.

Samples	Connected porosity (%)
S5	25.19
S6	12.11
S7	40.17
S8	44.43

(2006). The qualitative EDS analysis of the titanium powder does not indicate the existence of such elements added in the preparation of the samples in the metallography laboratory. Following the procedures of ASTM B963 (2014) (Moreira, 2013) the porosity connected to the surface of the sample (Table 4).

For the samples S5 and S6 produced solely from titanium powder, the compression pressure significantly influenced the result, reducing in half the percentage of porosity connected to the surface with the increase of this variable. The samples S7 and S8 reached levels slightly above 40%, the fact that evidence the interconnectivity of pores.

From the twenty images obtained from the optical microscope (Fig. 18) with the aid of ImageJ software, it was possible to construct an image of apparent surface porosity (Fig. 19).

The apparent porosity for Sample S6 was the lowest result found among the samples. Samples S7 and S8 have the highest percentages, in these cases, more than 50% of the sampled data are in the range of 60% to 70% of surface porosity.

Complementing SEM analysis of pore morphology, its size (between 100 µm and 600 µm) is an important variable to the structure for bone growth in its interior. Therefore, the average pore diameter was calculated using ImageJ software. There was difficulty in delimiting pore area of sample S5 due to porosity interconnectivity.

Only the samples S6, S7 and S8 were analyzed. The histograms (Fig. 20) demonstrate the results.

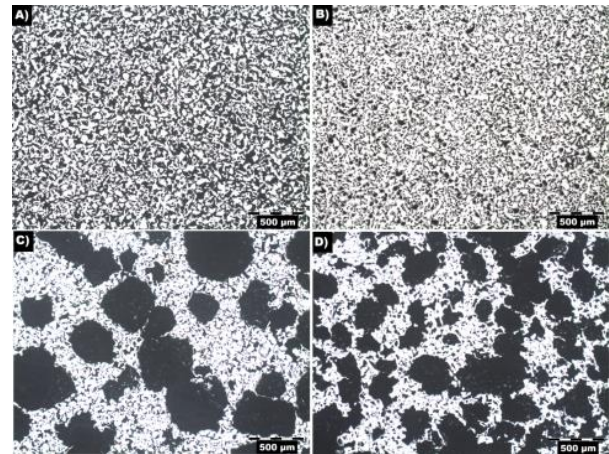


Fig. 18. Images obtained in the optical microscope. A) S5; B) S6; C) S7; D) S8.

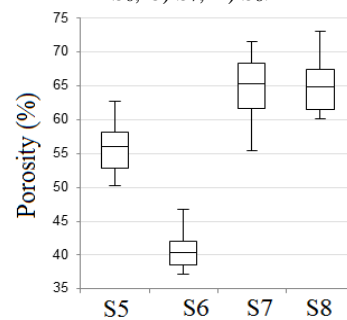


Fig. 19. Surface apparent porosity.

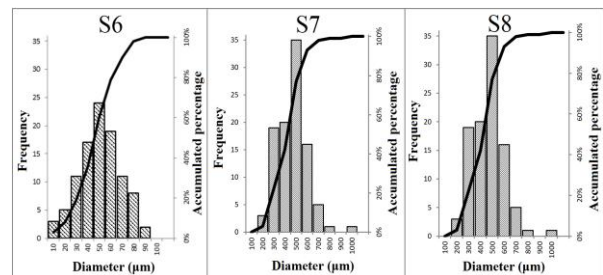


Fig. 20. Mean pore diameter of the samples.

With the collected data for the construction of the histogram, sample S6 has a mean porosity of 46.2 µm with a standard deviation of 16.9 µm, the same data for the sample S7 are mean of 419.7 µm and standard deviation of 133.1 µm. Finally, the sample S8 has an average of 396.1 µm and standard deviation of 166.8 µm.

Sample S6 shows irregular pores already found by SEM and sizes smaller than 100 µm (Fig. 20). Although not able to measure pore size for Sample S5, qualitatively they are mostly inferior to 100 µm, the resulting (irregular) surfaces provide an increase of roughness and area of contact between bone and implant, these characteristics improve the resistance of the union.

The pore size found at samples S4 and S5 does not allow invasive growth of hard tissue throughout the implant. Samples S7 and S8 show a macropore size of 100 µm to 600 µm, ideal size for good vascularization and bone reorganization. The connection between the macropores and micropores allows the growth of the membranes in its interior besides being able to provide a better biological development (osseointegration). It occurs



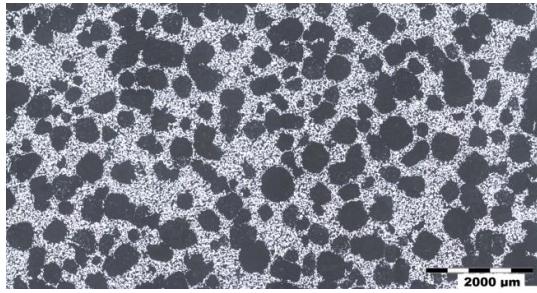


Fig. 21. Image obtained from optical microscope, Sample S<sub>7</sub>.

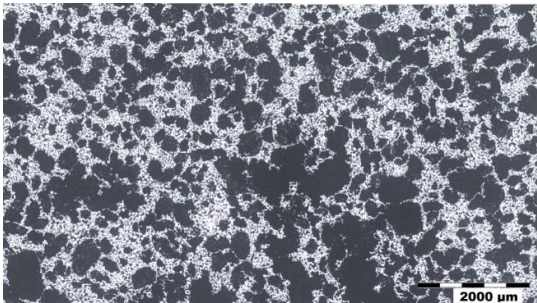


Fig. 22. Image obtained from optical microscope, Sample S<sub>8</sub>.

better and more durable interlock between metal and bone. This reduces relative movements between implant and membrane, bringing benefits such as the shorter recovery time of the individual post-surgical intervention.

It is not possible to conclude on the distribution of porosity in the matrix based on the magnification employed. However, the images (Fig. 21 and 22) provide better evaluation.

Sample S<sub>7</sub> shows morphology closer to spherical compared to Sample S<sub>8</sub> (Figs. 21-22). This difference is due to the compacting pressure of 250 MPa applied. By using pressures between 100 MPa, 200 MPa and 300 MPa, it forms more elongated porous morphology and apparent pore growth.

### III. CONCLUSIONS

For the particular case of Powder Metallurgy manufacturing applied only to pure titanium, it was not able to produce a porous structure suitable for bone growth in the interior. Compared with reported experiments with superficial porosity above 50% and interconnectivity between pores of 25% for the case of lower compaction pressure (Sample S<sub>5</sub>). Thus, samples made with only metallic powder do not demonstrate ideal pore sizes for bone development within the structure, even with the use of lower compaction pressure. The use of the space holder technique proved the possibility of controlling a structure with interconnected pores containing specific sizes for an excellent functionality, being able to apply a higher compression pressure, facilitating maneuvers without harming the geometry of the green compact. Sodium chloride provided pores with shapes closer to the spherical and better distribution in the specimen compared to ammonium bicarbonate, due to its cubic morphology, different from that of predominantly angular ammonium bicarbonate. With the same methods of sintering (Kennedy, 2012; Torres *et al.*, 2014), it is possible to state that the step of removing

ammonium bicarbonate is simpler and faster compared to sodium chloride.

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