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MECHANICAL BEHAVIOR OF TITANIUM DENTAL ALLOYS WELDED TO LASER AND PLASMA PROCESSES

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Abstract. *There is limited information in existing literature regarding the accomplishment of Ti-6Al-4V joints plasma and laser welded in prefabricated bars in different diameters. Therefore the aim of this study was evaluate the mechanical resistance of TI-6AL-4V alloy in different diameters (2.5, 3, 4 e 5mm) submitted to the processes of plasma and laser welding by means of tensile test and Finite Element Models. Forty-five dumbbell-shaped rods (n=5) with central diameters of 2.5, 3, 4 and 5 mm were created from Ti-6Al-4V prefabricated bars: CG(Control group) with 3 mm diameter, constituted by intact bars and PL2.5, PL3, PL4 and PL5 groups with 2.5, 3, 4 and 5 mm diameters submitted to plasma welding process and L2.5, L3, L4 and L5 groups with 2.5, 3, 4 and 5 mm diameters submitted to laser welding process. The plasma welding process was executed using current of 10 A and pulse of 3 ms and laser welding was executed using voltage of 365 V e pulse of 9 ms and the focus and frequency were calibrated at 0. The specimens were tested for tensile strength test until fracture and the percentage of elongation was obtained. Fractured samples were analyzed in stereomicroscope and the welded areas percentage was calculated. The most representative images were taken by tabletop scanning electron microscope in increases of 500 and 1200x. The results were evaluated by analysis of variance (ANOVA) and subsequently using Dunnet test to compare test groups to control group and the Tukey test to compare means of the test groups. Pearson and Spearman's correlation tests were applied for comparison of the parameters analyzed. The finite element models were developed in a Workbench environment with boundary conditions simulating a tensile test.*

Keywords: *Titanium; Dental Welding; Dental Alloys; Tensile Strength; Finite Element Method.*

1. INTRODUCTION

Currently, there are over 50 different welding processes that have some industrial use and they are considered the most important methods of permanent union of metals. This importance is further evidenced by the presence of welding and related processes in different activities (Marques *et al*., 2007), as aerospace, aviation, automotive (Cho *et. al.*, 2004), petrochemical, nuclear and medical (Akman *et. al*., 2008).

In dentistry, the welding between the abutments is carried out during the manufacture of the metal structure or even after the application of ceramics. This technique has been used by many dental surgeons to solve problems related to laboratorial distortions that end up resulting in prosthetic parts not properly adapted. The welding technique has the advantage of working with segments of the prosthesis, producing prosthetic structures with lower distortion, which allows a better adaptation to the abutments. This promotes a uniform distribution of forces while minimizing trauma or failures in the bone, in the implant or in the prosthesis (Chou and Chai, 1998; Tiossi *et al*., 2010).

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In addition, the recent and promising use of the titanium alloys (Ti) in dentistry has been driven by the need to produce structures of low weight and high resistance to masticatory forces (Hart and Wilson, 2006). Titanium has favorable mechanical and biological properties such as low density, excellent biocompatibility, good ratio weight / resistance and low modulus of elasticity (Williams, 1984; Wang and Welsch, 1995, Wang and Fenton, 1996, Taylor *et al.*, 1998; Chai and Chou, 1998; Liu *et al.*, 2002; Anusavice, 2005; Nuñez-Pantoja *et al.*, 2011). However, its high melting temperature, next to 1700°C, and high reactivity with nitrogen, hydrogen and oxygen from the air, when subjected to high temperatures make it more fragile. Therefore, it is necessary to use protective inert gas during the process, usually argon (Bergman, 1990, Craig *et al.*, 1997; Liu *et al.*, 2002; Topham and Watanabe, 2006).

Thus, the achievement of welded joints in dentistry has improved with the development and incorporation of knowledge from other fields such as engineering, which allowed the emergence of new techniques and equipment for the union of these welded joints, as an alternative to the conventional technique with blowtorch - Brazing (Marques, 2007; Simamoto-Junior, 2008), among which can be mentioned: laser welding and arc welding - TIG (Tungsten Inert Gas) welding and Plasma (Hart and Wilson, 2006).

In the welding processes TIG and Plasma, union is obtained through heating the materials by an arc established between a non-consumable tungsten electrode and the part to be welded (Taylor *et al*., 1998). The protection of the electrode and the zone to be welded is made by an inert gas, usually the argon (Rocha *et al*., 2006), or mixture of gases inert, argon and helium. Metal of addition can be used or not. Allows execution of high quality welds and excellent finishing, particularly in gaskets in small thickness, allows the welding on any position and presents excellent control of fusing puddle. Your basic equipment consists of a source of energy, Torch with tungsten electrode, source of shielding gas and an opening system the arc. The main difference between the solder TIG and the Plasma is the use of a nozzle constrictor that causes the concentration of the electric arc (Marques *et al*., 2007).

The laser welding is a joining process based on localized fusion of the joint through its bombardment by a beam of concentrated light, coherent and monochromatic high intensity (Marques *et al*., 2007). One of its biggest advantages is that it produces a Keyhole that concentrates the energy absorbed in a small region, resulting in high penetration and formation of narrow heat affected zone (HAZ) (Chai and Chou, 1998; Liu *et al*., 2002; Cho *et al*., 2003; Rocha *et al*., 2006; Srimaneepong *et al*., 2008; Nuñez-Pantoja *et al*., 2011).

It has been shown that this type of welding results in less distortion (Roggensack *et al*. 1993; Wang and Welsch, 1995; Chou and Chai, 1998; Srimaneepong *et al*., 2008; Pantoja-Nunez *et al*., 2010) compared with conventional welding methods. Besides having advantages such as the ability to perform laboratory procedure directly on the working model and expending less time working, optimizing steps needed for brazing technique.

The laser welding process is safe and can be performed close to the regions of resins and ceramics without the risk of damaging them (Gordon and Smith, 1970; Chou and Chai, 1998; Shimakura *et al*., 2009; Pantoja-Nunez *et al*., 2011) due to its small heat affected zone (Chai and Chou, 1998; Liu *et al*., 2002; Cho *et al*., 2003; Rocha *et al*., 2006; Srimaneepong *et al*., 2008; Nuñez-Pantoja *et al*., 2010), bonding strength of the weld compatible with the origin metal and preservation of the anatomy of the metallic infrastructure (Gordon and Smith, 1970). Moreover, the laser welding can be performed with or without addition metal. Its main disadvantages are concentrated in the high cost of equipment and initial difficulty in obtaining good quality welding (Marques *et al*., 2007).

However, certain limitations must be considered welding, since the welding processes are based on the application of heat or mechanical energy in the region of the joint, which tends to cause a number of unfavorable metallurgical and mechanical effects. These effects, together with the formation of discontinuities such as cracks and pores in the weld can affect the performance of welded components and cause premature failure of the structure (Maques *et al*., 2007).

Therefore, the objective of this study was to evaluate the mechanical strength of alloy Ti-6Al-4V in different diameters subjected to the processes of plasma and laser welding by means of tensile testing and Finite Element Method (FEM). Generating the hypothesis that the use of a domestic equipment micro-plasma welding can be used as an alternative to laser welding and that the increase in diameter positively influence the values of tensile strength.

2. MATERIALS AND METHODS

Forty five samples of Ti-6Al-4V alloy were manufactured in accordance with ASTM E8, as shown in Fig. 1a. The samples were divided into 9 groups ($n = 5$): CG (Control Group) with a diameter of 3 mm, consisting of bars intact; PL2.5, PL3, PL4 and PL5 groups, with diameters of 2.5, 3, 4 and 5 mm respectively, and welded with solder Plasma; and groups L2.5, L3, L4 and L5 with diameters of 2.5, 3, 4 and 5 mm, respectively, welded with laser welding. The plasma welding process was performed with a depth of 10 A and a pulse of 3 ms and the laser welding process was realized with a depth of 365 V and pulse of 9ms, with the focus and the frequency calibrated to zero.

The samples were subjected to tensile test in a universal testing machine with a speed of 0.02 mm / min until failure. The values of percentage elongation were obtained by subtracting the initial length of the final length and dividing the result by the initial length. The fractured samples were examined in a stereomicroscope and welded areas were calculated. The most representative images were evaluated in a scanning electron microscope (SEM) increases in 500 and 1200x.

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Finite element models were developed in the software Ansys Workbench® to simulate the tensile test on the samples, as shown in Fig 1b. The Ti-6Al-4V alloy was considered isotropic, elastic and continuous. The elastic modulus and Poisson's ratio of the metal base structures were 0,96 GPa and 0,35, respectively. The value of the modulus was increased by about 20% for the weld area. The force was applied in the direction of the z axis in one of the lateral faces of the sample. On the other face of the structure was applied the displacement restriction, considering the fixed support. The force values used in the simulation were based on tensile tests. Data were obtained from on the z axis displacement (mm) and maximum principal stress (MPa). The values of the force applied to test tensile strength of intact specimens were used as a reference for computer simulation. The values of stress and displacement from the numerical models were compared with the experimental stress and displacement values. As the results were close, the finite element model was validated.

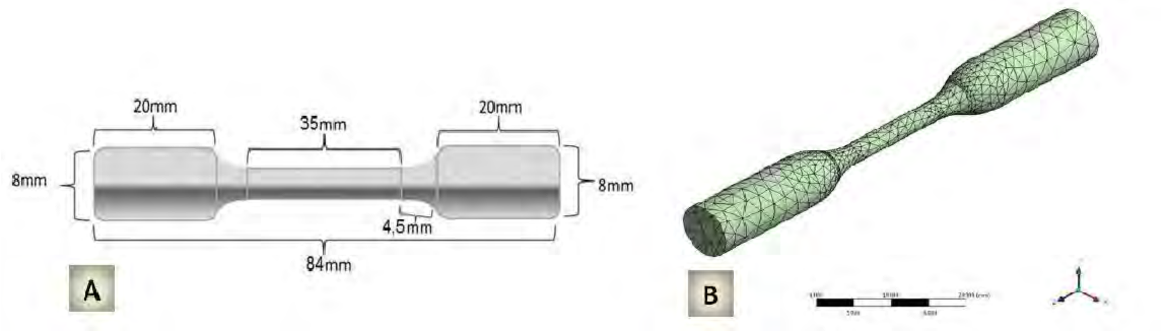

Figure 1. a) Dimensions of the test specimen (ASTM E8), b) Numerical model with elements and nodes.

3. RESULTS

3.1. Plasma Welding

Table 1 shows the mean values and the standard deviation for the maximum stress. The control group (1008,46 +37,1) had higher maximum stress than the experimental groups. The experimental group PL2.5 (627,32 +94,18) and PL3 (571,54 +108,64) showed the highest values of maximum stress and the group PL5 (320,6 +38,68) had the lowest values.

Table 1. Values of maximum stress (Mpa).

Group	Control	PL2.5	PL3	PL4	PL5
Mean	1008,46^{A}	627,32^{B}	571,54^{BC}	434,82^{CD}	320,6^{D}
Standard deviation	37,1	94,18	108,64	79,64	38,68

The mean and standard deviation of the percentage of elongation are shown in Tab. 2. The mean values for elongation percentage of all test groups range from 0,38% (group PL4) to 1,62% (group PL5). The average for the control group was 7,48%. There was statistically significant difference between the control and experimental groups, but there was no statistical difference between the experimental groups.

Table 2. Percentage of elongation (%).

Group	Control	PL2.5	PL3	PL4	PL5
Mean	7,48^{A}	1,60^{B}	1,44^{B}	0,38^{B}	1,62^{B}
Standard deviation	1,18	1,02	0,94	0,32	0,93

As the samples a and b have previously been numbered and all samples fractured in the weld region, the values were described in 1a, 1b, 2a, 2b and so on. It was observed the statistically significant differences between the test groups. PL2.5 groups (47,93 +1,89) and PL3 (43,80 +2,46) had the largest percentage values of the welded area and PL5 group (26,60 +1,89) the lowest. The mean and standard deviation for percentage of welded area are described in Tab. 3.

Table 3. Percentage of welding area (%).

Group	PL2.5	PL3	PL4	PL5
Mean	47,93^{A}	43,80^{AB}	36,66^{B}	26,60^{C}
Standard deviation	1,86	2,46	6,06	1,89

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The figures below refer to images obtained in Stereoscopic Magnifier and Scanning Electron Microscope (SEM) for the specimens welded with welding Plasma after tensile test. Figure 2 shows cross-sectional images of the specimens welded after the tensile test, showing that the weld does not penetrate the entire diameter of the test specimen, leaving the center of the sample without welding and this finding was consistent for all samples.

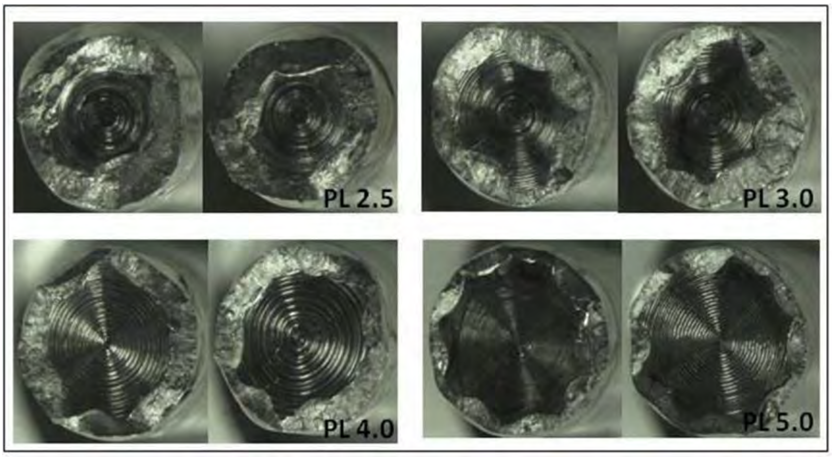

Figure 2. Images obtained by stereomicroscopy.

Figures 3a and 3c show SEM images of the fracture area of the weld with increased 500x. Figures 3b and 3d show SEM images with increased 1200x. They reveal that the fracture in the TI-6AL-4V alloy has a generally flat surface and has regions with a honeycomb shape, characteristic of titanium and fragile fractures. In addition, the fracture has surface undulations that are more elevated areas in relation to the plane, called dimples, which indicate a small ductility. We observed also some failures like bubbles and porosities, indicated by the red arrows.

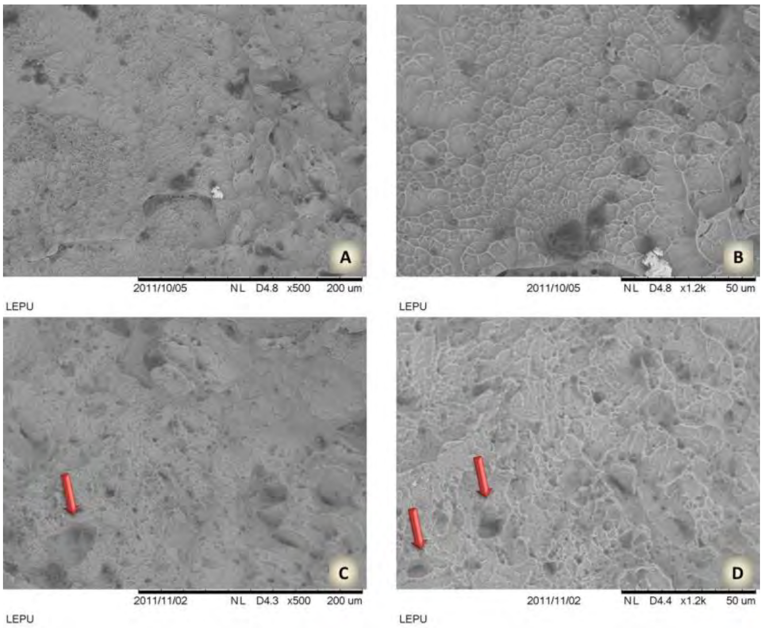

Figure 3. a) and b): Images obtained in SEM for the samples in the group PL3 at 500x and 1200x, respectively, c) and d): Examples of the SEM images for the samples in group PL5 at 500x and 1200x, respectively.

3.2. Laser Welding

It was noted that the control group (1008,46 +37,1) showed higher maximum stress than the experimental groups. Within the experimental groups, the group L2.5 (762,94 +133,57) and L3 (601,93 +232,99) showed higher maximum stress and the group L4 (542,78 +179,98) and L5 (515,57 +154,23) had the lowest values. The mean values and standard deviation for the maximum tension are described in Tab. 4.

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Table 4. Values of maximum stress (Mpa).

Group	Control	L2.5	L3	L4	L5
Mean	$1008,46^{A}$	$762,94^{B}$	$601,93^{BC}$	$542,78^{C}$	$515,57^{C}$
Standard deviation	37,1	133,57	232,99	179,98	154,23

The mean and standard deviation of the percentage of elongation are present in Tab. 5. The values for all test groups ranged from 0,78% (group L5) to 1,98% (group L2.5), and the average for the control group was 7,48%. It was observed statistically significant difference between the control and experimental groups, but there was no statistical difference among the experimental groups.

Table 5. Percentage of elongation (%).

Group	Control	L2.5	L3	L4	L5
Mean	$7,48^{A}$	$1,98^{B}$	$1,07^{B}$	$1,01^{B}$	$0,78^{B}$
Standard deviation	1,18	1,88	0,77	0,32	0,31

Table 6 shows the mean values and standard deviations of the percentage of the welded area. The samples were previously defined as 'a' and 'b' and all samples had complete rupture, thereby the values were described in 1a, 1b, 2a, 2b and so on. Statistically significant difference was observed among the test groups. PL2.5 (73,21 +8,03) and PL3 (70,91 +8,02) groups had the largest percentage values of the welded area and PL4 (56,03 +2,80) and PL5 (52,57 +7,48) group showed the lowest values.

Table 6. Percentage of the weld area (%).

Group	L2.5	L3	L4	L5
Mean	$73,21^{A}$	$70,91^{A}$	$56,03^{B}$	$52,57^{B}$
Standard deviation	8,03	8,02	2,80	7,48

The Figures 4 and 5 refer to images of the specimens welded with laser welding after the tensile test, which were obtained in the Stereoscopic Magnifier and in the Scanning Electron Microscope (SEM). Figure 4 shows cross-sectional images of the specimens welded after the tensile test. The images show that the weld does not penetrate across the diameter of the test specimen. Thus, the central region of the sample is not welded, which occurs in all samples.

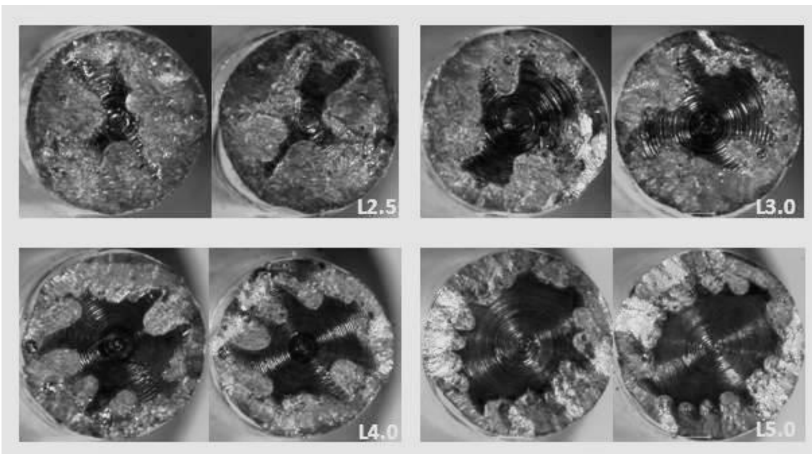

Figure 4. Images obtained through stereoscopic magnifier.

Figures 5a and 5c show SEM images of the fracture area of the weld increased 500x. Figures 5b and 5d show SEM images with increased 1200x. They reveal that the fracture in the TI-6AL-4V alloy has a generally flat surface, regions with a beehive-shaped, which are characteristic of titanium and more characteristic of a fragile fracture. Furthermore, it contains surface undulations (more elevated areas in relation to the plane), called dimples, which indicates a small amount of ductility. In addition, some failures can be seen as bubbles and porosities that are highlighted by red arrows.

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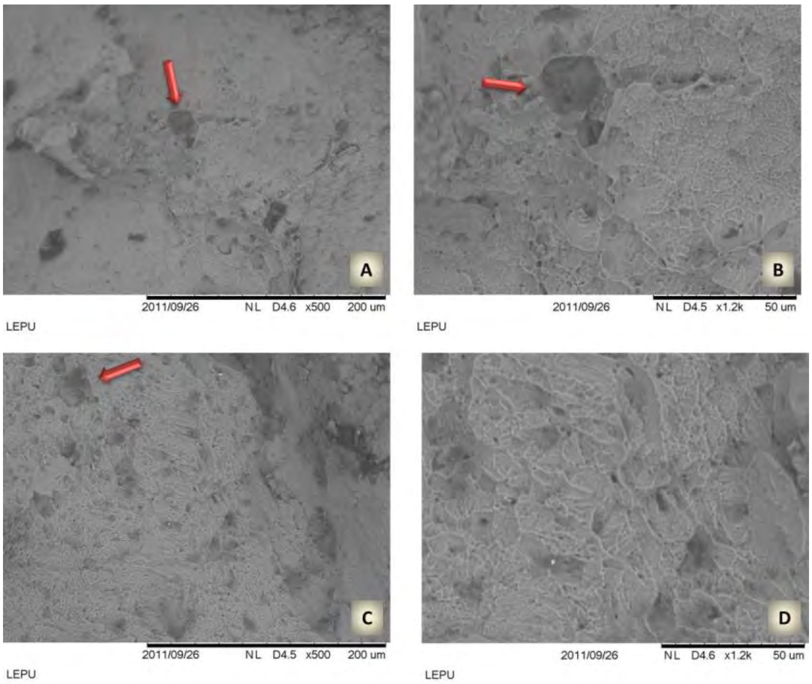

Figure 5. a) and b): Examples of SEM images of the samples of the L2.5 group in at 500x and 1200x, respectively, c) and d): Examples of SEM images of the samples L5 group in at 500x and 1200x, respectively.

3.3. Plasma Welding x Laser Welding

Comparisons of the maximum stress values obtained by the process of laser welding and plasma welding were made. It was observed that there was no statistical difference between the different types of welding for all diameters of specimen tested, as can be seen in Tab. 7.

Table 7. Mean values + standard deviation of maximum stress for different types of welding and different diameters.

Process of welding	Diameter (mm)			
	2,5	3,0	4,0	5,0
Laser	762,95+133,58[a]	601,93+232,99[a]	542,78+179,98[a]	515,57+154,24[a]
Plasma	627,32+94,18[a]	571,54+108,64[a]	434,82+79,64[a]	320,60+38,68[a]

The results for the elongation showed no statistically significant difference between the different types of welding for the experimental groups with diameters of 2.5, 3 and 5 mm. The difference was statistically significant only for the group with diameter of 4mm as shown in Tab. 8.

Table 8. Mean values + standard deviation of elongation percentage for different types of welding and different diameters.

Process of welding	Diameter (mm)			
	2,5	3,0	4,0	5,0
Laser	1,98+1,88[a]	1,07+0,77[a]	1,01+0,32[a]	0,78+0,31[a]
Plasma	1,60+1,02[a]	1,44+0,94[a]	0,38+0,32[b]	1,62+0,93[a]

For the values of the welded area was statistically significant difference between the different types of welding for all experimental groups, as can be observed in Tab. 9. Groups welded by laser process had higher percentages of welded area when compared to groups of plasma welding.

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Table 9. Mean values + standard deviation of percentage of the welded area for different types of welding and different diameters.

Process of welding	Diameter (mm)			
	2.5	3.0	4.0	5.0
Laser	73,21+7,85[a]	70,91+6,85[a]	56,03+2,56[a]	52,57+7,88[a]
Plasma	47,93+5,44[b]	43,80+6,27[b]	36,64+4,92[b]	26,61+1,41[b]

3.4. Finite Element Method

Figure 6 shows the stress-strain curves for the control group, made without any weld, which were obtained from the experimental tests and from the simulation by finite element method. Analyzing the stress-strain graph, it is observed that the curves of experimental results and numerical overlap. The curve of the control group given by the experiment shows a ductile behavior with points in elastic and plastic phases. The numerical model is valid only in the elastic phase, so the points of the plastic were not evaluated in MEF.

The displacement along the entire specimen is shown in Fig. 7a. Based on the Figure 7b, it was observed that there was a stress concentration along the central region of the sample, which showed that the rupture could occur at any point in this region.

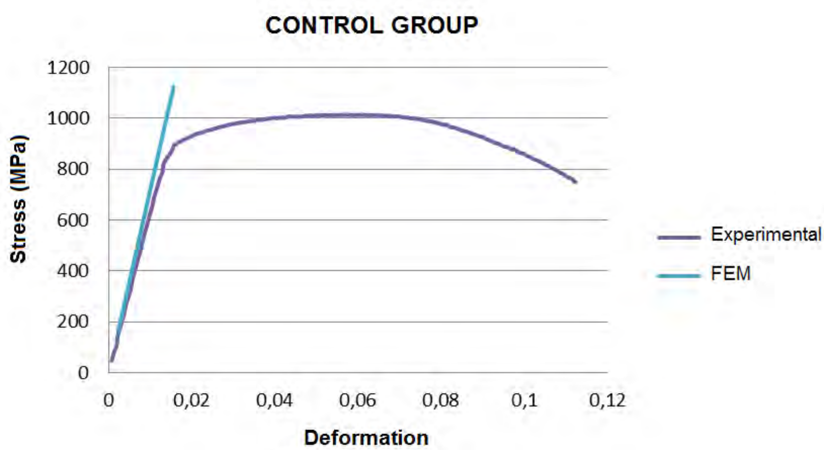

Figure 6. Graph of stress x deformation for the control group evaluated by experimental tests and the finite element models.

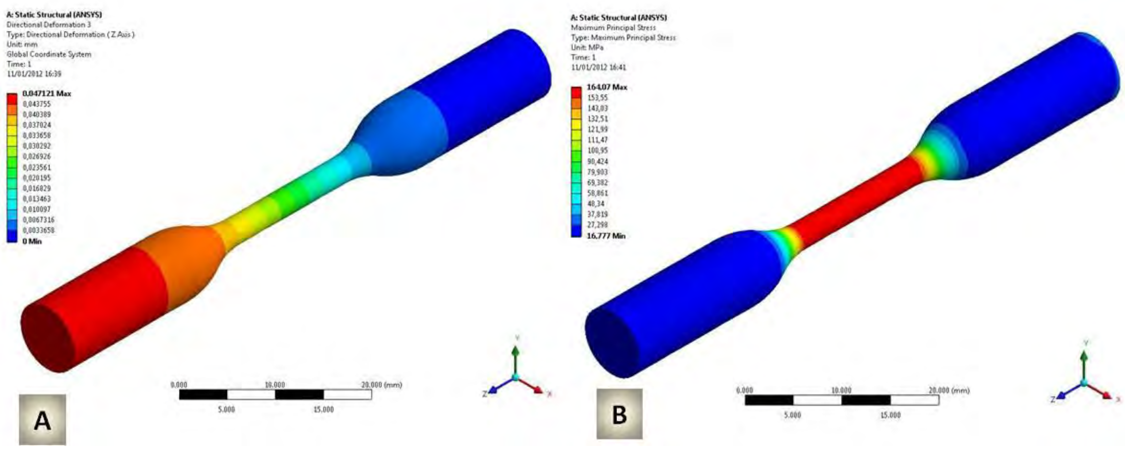

Figure 7. Models for the control group. a) Representative image of directional deformation along the Z axis, b) Representative image of principal maximum stress for the intact samples.

The graph of stress x deformation for specimens welded by the plasma welding process, given in Fig.8, shows nearby curves of the experimental group and the FE model. Figure 9 shows the graph of stress x deformation for specimens welded by laser welding process, it is possible to note a similarity between the curves of the experimental

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group and the FE model. However, adjustments to the numerical model as the geometry and material properties in the weld area, are necessary. Though these models are simplified, can be used to represent the welded specimen through the plasma and laser welding.

It can be seen that was a displacement along the entire specimen with plasma and laser welding, Fig 10a and 11a, respectively. It is observed by Figure 10b and 11b that was a stress concentration in the region corresponding to the welding in the sample, showing that the rupture could occur in this area.

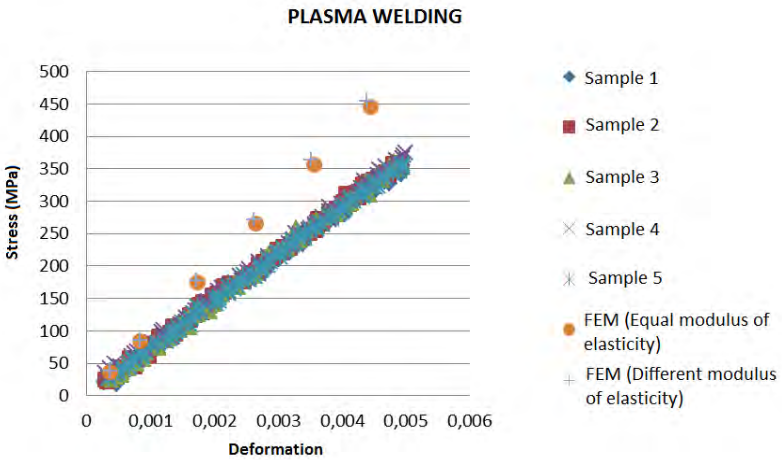

Figure 8. Graph of stress x deformation for the experimental tests and the finite element model.

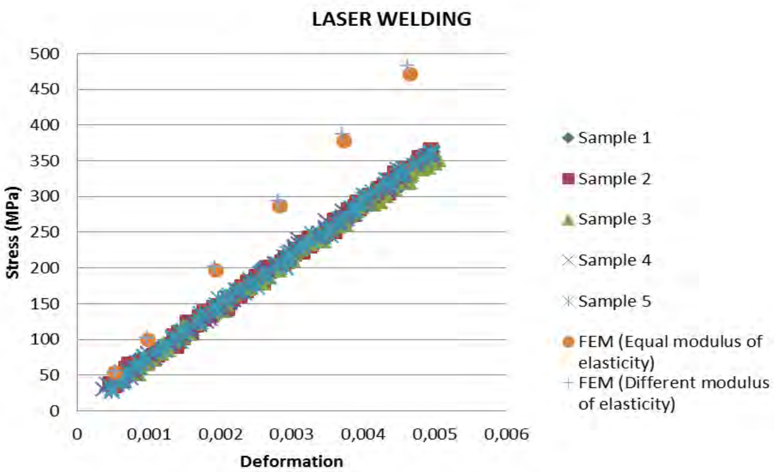

Figure 9. Graph of stress x deformation for the control group and the finite element model.

4. DISCUSSION

The results showed that the maximum stress values in the control group were higher than those groups subject to laser welding and plasma welding, independent of the diameter of the samples. This result contradicts some studies (Roggensack *et al*., 1993; Berg *et al*., 1995; Neo *et al*., 1996; Liu *et al*., 2002; Srimaneepong *et al*., 2008), which stated that the mechanical strength of welded joints has a value similar to or higher than the base metal of the intact specimens, under suitable conditions of welding. The numerical models showed that in the control group stress concentration is located across the central part, while the stress in the welded groups is concentrated on the welding region. Under optimal conditions the models should present similar behaviors, meaning that the fracture could occur in any region of the base metal as well as in the control group.

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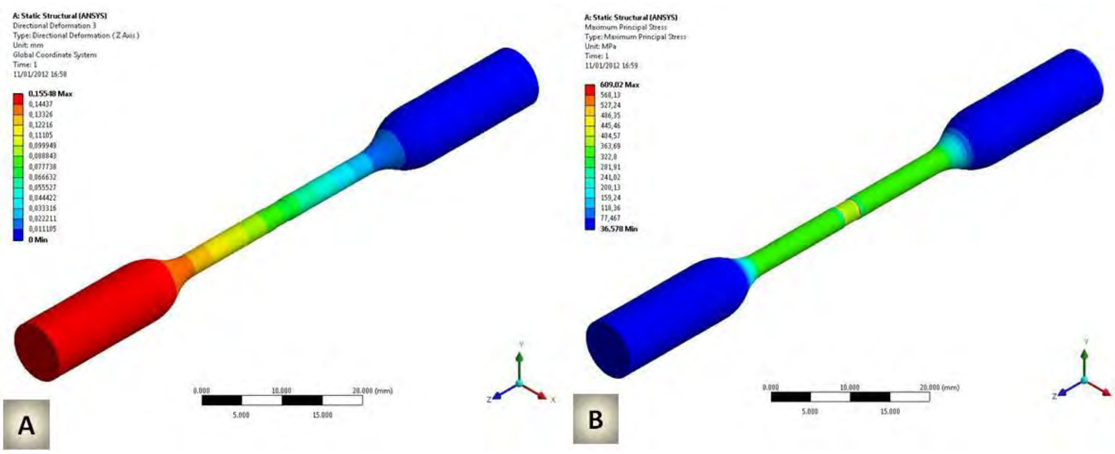

Figure 10. Numerical model of the samples with plasma welding. a) Representative image of directional deformation along the Z axis, b) Representative image of principal maximum stress for the intact samples.

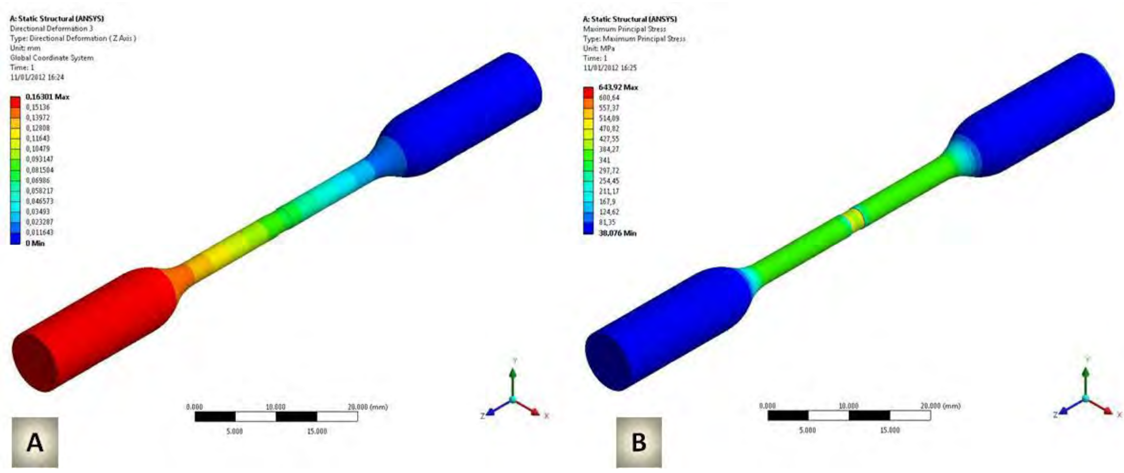

Figure 11. Numerical model of the samples with laser welding. a) Representative image of directional deformation along the Z axis, b) Representative image of principal maximum stress for the intact samples.

Several factors, resulting from the process used, contributed to achieving such results. One factor relates to the processes of electric arc welding which is characterized by the imposition of large amount of localized heat. The localized heat fusion allows the addition material and the base material, producing significant microstructural transformations. These transformations occur in a region called the heat affected zone (HAZ), the region of the base metal whose structure or properties were changed by varying the temperature during welding (Botega 2005; Meadows and Fritz, 2005). Changes generate complex stresses and deformations, leading to results not always desired, such as distortion of the material, residual stresses, generating microstructures fragile, grain growth, cracks, and changing of mechanical, physical and chemical properties, among others (Ramirez *et al*., 2005).

Welded joints by laser welding also suffer from defects resulting from residual stress, among other reasons. Normally, residual stress introduced in the welded regions is a consequence of the thermal stress caused by cycles of heating and cooling in the welding process. Therefore, it affects the mechanical behavior of the laser welded structures (Cho *et al*., 2003).

Another influencing factor is the high affinity that titanium has with oxygen, hydrogen and nitrogen free, in the high temperatures reached during welding. These elements are aggregated at the structure, by making it rich in impurities (Roggensack *et al*., 1993; Botega, 2005). Thus, there is a reduction in ductility and tensile strength of the material (Chou and Chai, 1998; Botega, 2005), even when welding is performed with the inert gas protection.

The reduction of ductility (Berg et al., 1995) can be observed in the images obtained under SEM, presented in Fig.4. They show that the fracture surfaces of the samples have generally planar surface undulations indicating a small ductility, called dimples (Sjögren *et al*., 1988; Wang and Welsch, 1995; Botega, 2005). The reduction of this property, it can also be proven by the percentage of elongation of the samples, since the average values of percentage elongation for the control group showed statistically significant difference ($p<.05$) compared to the experimental groups and above these. However, a specimen broke in the region of the base metal and not in the welded joint, showing percentage elongation (5,11%) higher than the other specimens in the same group.

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Berg *et al.* (1995) describe the porosity and bubbles generated during the laser welding process are responsible for the reduction in the values of tensile strength of welded groups compared to the control group. In addition, states that the value of tensile strength of the material depends more on the occurrence of failures that the material properties of the weld region. The porosities in the region of the union occur due to the inclusion of argon gas, required to maintain the inert atmosphere during the welding procedure (Topham and Watanabe, 2006; Roggensack *et al.* 1993; Zavanelli *et al.*, 2004; Botega, 2005; Nuñez -Pantoja *et al.*, 2011). In Figure 5, the SEM images show the bubbles and porosities existing in the specimens welded.

These bubbles and porosities work as initiators of fracture, since they act as stress concentration points. They can lead to failure welded structure in a short period of time under application of stresses lower than those supported by an appropriate coupling (Neo *et al.*, 1996). In the absence of imperfections, fracture should occur in the base metal, meaning that the entire joint has been completely welded (Berg *et al.*, 1995). This occurred in the specimen number 2 from the group L2.5, in which the rupture of the specimen occurred in the base metal and not on the weld region, suggesting that the entire cross section was welded without fail.

The values of tensile strength were lower for the welded groups than for the control group may be due to an incomplete union, generated by insufficient penetration of the weld (Wang and Welsch, 1995). According to some authors (Chai and Chou, 1998; Liu *et al.*, 2002), the penetration depth of the weld is the main factor that affects the values of mechanical strength of laser welded structures.

When the laser weld penetration is insufficient, a large bubble or internal failure occurs (Baba & Watanabe, 2005; Nuñez-Pantoja et al., 2011). This was observed in the images of stereoscopic magnifier for plasma welding and laser welding, mainly for samples of larger diameter. Similar images were found by other authors such as Sjögren *et al.* (1988), Welsch and Wang (1995), Neo *et al.* (1996) and Botega (2005).

Thus, one hypothesis that motivated this study was rejected because the increase in diameter negatively influenced the tensile strength and the percentage area of welded samples. However, these values were obtained for a same setting of the machine, which for plasma welding was 10 A and 3ms and for laser welding was 365V and 9 ms.

The energy level of the laser welding process can be controlled by the parameters: voltage or current, and pulse duration (Chai and Chou, 1998). The voltage controls the welding potency and an increase in voltage leads to a greater depth of penetration of the weld. The duration of the pulse determines the diameter of the spot weld that will be greater the higher the pulse duration used (Chou and Chai, 1998; Baba and Watanabe, 2004). However, the current or voltage has a greater influence on the strength values than the pulse duration (Chou and Chai, 1998).

However, when the intensity of laser welding is exceeded and the power supply is prolonged, the temperature of the melted metal exceeds the melting point and causes the molten metal evaporates. The increase in the volume of evaporated metal in comparison with the molten metal causes a high pressure. The pressure of the evaporated metal creates turbulence in the molten metal and forms a cavity, called keyhole (Baba and Watanabe, 2004). Thus, in situations favorable the weld penetration is optimized, however in these cases of high levels of energy structure can be damaged superficially. On the other hand, these superficial structural alterations may not be the most important compared to the tensile strength. Therefore, the high voltage values can be used for larger diameters to obtain sufficient depth of weld penetration in prosthetic structures.

Some authors (Chai and Chou, 1998; Liu *et al.*, 2002) found that the penetration depth of laser welding for titanium was proportional to the current or voltage and that the elongation and tensile strength were significantly influenced by this parameter. Thus, for best results, especially for larger diameters, the adjustment of the equipment is essential (Sjogren *et al.*, 1988; Roggensack *et al.*, 1993). Despite the existence of numerous studies on laser welding in the literature, there is still no established protocol welding (Nuñez-Pantoja *et al.*, 2011).

The configuration of the welded joint can also influence the results. The type of joint used in this study seems not suitable for the larger diameters of 4 and 5mm, due to the limited welding energy of welding machines used in dentistry. Possibly a gasket in the shape of 'X' would be more appropriate because the center is maintained juxtaposed and allows the weld penetration depth (Zupancic et al. 2006).

Regarding the welding method, it was found in this study that the values of tensile strength of the samples welded with plasma and laser welding showed no statistically significant differences between each other within each diameter analyzed. Also, have similar advantages as: allow the weld in the own model; allow welding in areas close to the resin and porcelain; allow welding in any position and require less time of work of the professional (Baba & Watanabe, 2004; Rocha et al ., 2006).

It was found that the plasma welding can be used as an alternative to laser welding, which has a high equipment cost and may decrease the value of rehabilitation and treatment optimization. Thus, another hypothesis that motivated the work was accepted. It should be noted that the plasma technique is more sensitive when compared to laser technique. Note that the laser group shows no statistically significant difference in the plasma group, but has more uniform results in all diameters.

However, this accepted hypothesis may not be taken as a result completely conclusive, since the maximum stress values considered in this study were the values offered by the testing machine that considers the strength of the entire cross section. For future studies, the maximum stress values obtained from experimental tests should be estimated by considering only the area resistant tensile (area effectively welded). It is expected that this procedure to modify the stress x deformation curves for various specimens analyzed.

In addition, there are forces in clinical conditions which have not been simulated in the tests, as other masticatory forces and consequential parafunction. Another limitation of this work concerns the computational models. The characterization and evaluation of mechanical strength and biomechanical behavior of welded structures in dentistry can be made using modeling EF. However, the numerical models are limited due to the nonlinearities of the process, as the variation of mechanical behavior in the region of the weld and the definition of a geometric model that characterizes the welded region, which should be further explored in future work. Besides the formation of micro-voids, internal corrosion effects, variations in the welding area depending on the material strength versus weld parameters and influence of the environment and the process.

In this study, the proposal was to introduce some changes in geometry and modulus of elasticity in order to model numerically the welded region. In this case, the evaluation of this model was made considering the results of tensile tests for plasma and laser processes. This first model developed considers the entire cross-section welded. In this case, the boundary conditions and geometry were modified in order to adjust the values of stress x deformation in the elastic phase. Thus, new numerical models representing the effective weld area should be developed with new geometries and boundary conditions to adjust the values of stress x deformation.

Although the alloy Ti-6Al-4V has been used in this work because of their chemical, biological and mechanical conditions (Williams, 1984; Wang and Welsch, 1995; Wang and Fenton, 1996; Taylor *et al.*, 1998; Chai and Chou, 1998; Liu *et al.*, 2002; Anusavice, 2005; Nuñez-Pantoja *et al.*, 2011), other alloys can be used for evaluation and compared with the results obtained in this work.

5. CONCLUSION

Within the limitations of this study, the diameter of 2.5 mm and 3.0 mm showed higher tensile strength and percentage of welded area, both for plasma welding and for welding laser. These samples appear to be the best option for joining prefabricated bars for use in prosthetic structures. The plasma welding equipment seems to be an alternative to laser welding equipment, no significant statistical differences between the types of welding for each diameter.

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8. RESPONSIBILITY NOTICE

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