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# Estudo da qualidade da fundição do Titânio comercialmente puro e da união soldada a laser em estruturas de Ti cp e em liga de Ti-6Al-4V

Dissertação apresentada à Faculdade de Odontologia de Piracicaba da Universidade Estadual de Campinas, para obtenção do título de Mestre em Clínica Odontológica - Área de concentração em Prótese Dental.

**Orientador: Prof. Dr. Marcelo Ferraz Mesquita**

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“A vida é como andar de bicicleta. Para manter o equilíbrio, é preciso se manter em movimento”

Albert Einstein

# RESUMO

O objetivo desse estudo foi: 1) Examinar por meio de radiografias, a incidência de porosidade interna em estruturas fundidas em titânio comercialmente puro, com diferentes diâmetros de secção transversal; 2) Analisar essa incidência em uniões soldadas a laser, com diferentes distâncias de soldagens, em espécimes de Ti cp e Ti-6Al-4V, variando o diâmetro da secção transversal; 3) Avaliar a resistência à fadiga dessas uniões e correlacionar esses achados com os resultados das analises radiográficas das uniões. Para a primeira análise, 60 halteres (n=20) com diâmetro de 1,5; 2,0 e 3,5 mm de secção transversal foram fundidos em Ti cp, por meio da técnica da cera perdida utilizando-se o sistema Rematitan. Os halteres receberam acabamento e polimento e foram submetidos à análise radiográfica (90 KV, 15 mA, 0,6 segundos e 10 a 13 mm de distância) com filme periapical. As radiografias foram analisadas visualmente quanto à presença de porosidade interna em toda a extensão dos halteres, e apenas na porção do diâmetro central. Os resultados foram submetidos ao teste Qui-quadrado (5%). Foi possível visualizar essas porosidades na maioria (91,7%) dos espécimes fundidos, especialmente nos de diâmetros mais delgados. Para a análise radiográfica das uniões soldadas a laser em espécimes de Ti-6Al-4V, 60 halteres com as mesmas dimensões foram usinados em liga de Ti-6Al-4V. Os halteres foram seccionados e soldados utilizando duas distâncias de soldagem (0,0 e 0,6 mm). O cruzamento das variáveis (distância e diâmetro) gerou seis grupos (n=10). A soldagem a laser foi realizada utilizando-se 360V/8ms (1,5 e 2,0 mm) e 380V/9ms (3,5 mm), com foco e freqüência regulados em zero. As uniões receberam acabamento e polimento e foram submetidas à idêntica análise radiográfica, verificando-se a presença de porosidades internas nas uniões. Os resultados, analisados pelo teste Qui-quadrado (5%), permitiram afirmar que é possível visualizar porosidade nas uniões analisadas. Para halteres de 1,5 mm, a incidência foi maior quando a distância entre as partes soldadas era 0,6 mm; ao contrário, para espécimes de 3,5 mm, essa incidência nessa distância foi menor. Para as análises radiográficas das uniões no Ti cp, 60 halteres fundidos e isentos de porosidade interna na região do diâmetro central, com as mesmas dimensões, foram seccionados, soldados e analisados da mesma maneira que para os espécimes de Ti-6Al-4V, sendo possível visualizar poros nas uniões. Em espécimes delgados (1,5 e 2,0 mm), a incidência de porosidade é maior quando a abertura da junta é maior. Entretanto, para espécimes de 3,5 mm a incidência é alta para ambas as distâncias de soldagem, sem diferença estatística. Para o estudo de resistência à fadiga das uniões em Ti-6Al-4V, os mesmos espécimes soldados que foram utilizados no segundo estudo, associados a espécimes intactos formaram 9 grupos (n=10). Esses espécimes foram submetidos a ensaios de ciclagem mecânica e o número de ciclos resistidos até a fratura foi registrado. A superfície de fratura foi examinada por meio de microscópio eletrônico de varredura (MEV). Os testes de Kruskal-Wallis e Dunn (5%) indicaram que o número de ciclos necessários para a fratura foi menor para todos os espécimes com distância de 0,6 mm, e para os espécimes de 3,5 mm distância 0,0 mm. O coeficiente de Spearman (5%) indicou correlação negativa entre número de ciclos e presença de porosidade nas radiografias. Finalmente, para a análise de resistência à fadiga das uniões no Ti cp, os mesmos halteres soldados do terceiro estudo associados a halteres intactos foram submetidos a similares ensaios mecânicos que os realizados no quarto estudo. Os números de ciclos necessários para a fratura foram registrados e a superfície fraturada, examinada igualmente, podendo-se tecer conclusões similares. Assim, concluiu-se que a qualidade das uniões é melhor quando espécimes mais delgados são soldados com justaposição das partes; e que a análise radiográfica é eficiente para se checar a presença de porosidades internas em espécimes fundidos e em uniões soldadas a laser.

**Palavras Chave:** Titânio; Soldagem em Odontologia; Radiografia Odontológica; Próteses e Implantes; Fadiga; Técnicas de Fundição Odontológica.

# ABSTRACT

The aim of this study was: 1) To exam radiographically internal porosity incidence in pure titanium (CP Ti) specimens casted in different diameters; 2) To verify the same incidence in laser welded joints executed in Ti-6Al-4V specimens and CP Ti specimens, within several diameters and joint openings; 3) To evaluate all these joints fatigue strength and correlate these results with the results of joints radiographic analyses. To first analysis, 60 dumbbell rods (n=20) with central diameters of 1.5, 2.0 and 3.5 mm were prepared by lost-wax casting procedure with the Rematitan System, using CP Ti. The casting specimens were finished, polished and submitted to radiographic examination (90 KV, 15 mA, 0.6 second and 10 to 13 mm of distance) with periapical film. The radiographies were visually analyzed for the presence of porosity in the entire extension of the dumbbell and just in its central part. Data were submitted to Chi-Square test (5%). It was possible to visualize internal porosity in CP Ti castings in most of the specimens (91.7%), particularly in the small diameter specimens. To radiographic analysis of Ti-6Al-4V joints, 60 dumbbells rods with the same dimensions were machined from Ti-6Al-4V wrought bars. Specimens were sectioned and welded using two joint openings (0.0 and 0.6 mm). The combination of the different diameters and joint openings created six groups (n = 10). Laser-welding was executed using 360V/8ms (1.5 and 2.0 mm) and 380V/9ms (3.5 mm) with the focus and frequency regulated at zero. The joints were finished, polished and submitted to identical radiographic examination. The radiographs were visually analyzed for the presence of porosity in the dumbbells joints. Data were submitted to the Chi-Square test (5%). Results demonstrated that it is possible to visualize porosity in the joints analyzed. For the 1.5 mm specimens, the incidence was higher when the 0.6 mm joint openings were used; conversely for the 3.5 mm specimens, the incidence of internal porosity was lower for the 0.6 mm joint opening. To radiographic investigation of CP Ti joints, 60 CP Ti casted dumbbell rods, free of internal voids in diameter extension, in the same diameters were sectioned, welded and analyzed the same way as Ti-6Al-4V specimens. Herewith, it was possible to visualize internal porosity in the joints. In thin specimens (1.5 and 2.0 mm), the porosity incidence is higher when the joint distance is larger. However, in 3.5 mm specimens, the incidence is high for both joint openings, without statistical difference. To Ti-6Al-4V joints fatigue strength study, the same laser-welded specimens analyzed in second study associated with the intact specimens made a total of 9 groups (n=10). These specimens were submitted to mechanical cyclic tests, and the number of cycles until failure was recorded. The fracture surface was examined with a scanning electron microscope (SEM). Kruskal-Wallis and Dunn test (5%) indicated that the number of cycles required for fracture was lower for all the diameters with joint openings of 0.6 mm, and for 3.5 mm diameter for the 0.0 mm joint openings. The Spearman correlation coefficient (5%) indicated a negative correlation between number of cycles and presence of porosity in radiographies. To CP Ti joints fatigue strength test, the last study, the same laser-welded specimens analyzed in third study associated with the intact specimens were submitted to similar mechanical cyclic test than fourth study. The number of cycles until failure was either recorded and the fracture surface was examined the same way. Conclusions can be weaved similar the anterior study. Within the limitations of these studies, it could be concluded that joints quality is better when thin specimens are welded with no distance among welding parts; and that radiography analyzes are efficient to check internal porosity in casted specimens and in laser-welded joints.

**Key Words:** Titanium; Dental Soldering; Dental Radiography; Prostheses and Implants; Fatigue; Dental Casting Technique.

# SUMÁRIO

# 1. INTRODUÇÃO

Bränemark e colaboradores, nas décadas de 50 e 60, iniciaram e desenvolveram a Implantodontia, o que permitiu a existência de uma alternativa viável para as reabilitações com Próteses Fixas e Removíveis confeccionadas tradicionalmente sobre dentes naturais (Jemt & Linden, 1992). Devido ao alto índice de sucesso, cada vez é mais freqüente a utilização de implantes para a confecção de próteses fixas ou removíveis, unitárias ou múltiplas. Isso devido à preservação de estruturas dentais adjacentes sadias, ou à melhora na retenção e estabilidade das próteses totais removíveis (Neo *et al.*, 1996).

Inicialmente, infra-estruturas protéticas eram confeccionadas a partir de metais nobres, mas devido ao alto custo dos mesmos passaram a ser substituídas por metais não nobres. Entretanto, estes apresentavam algumas desvantagens, tais como baixa resistência à corrosão, insuficiente adaptação cervical e possíveis reações alérgicas causadas por elementos como níquel e berílio. Com o advento da Implantodontia, iniciaram-se estudos a respeito do uso do titânio e suas ligas na construção das infra-estruturas. Esse metal apresenta características favoráveis, tais como biocompatibilidade, elevada resistência à corrosão, baixo custo, propriedades mecânicas favoráveis, baixa densidade e baixa condutibilidade térmica (Taira *et al.*, 1989; Craig *et al.*, 1993; Lautenschlager & Monaghan, 1993; Wang & Fenton, 1996; Chai & Chou, 1998), o que fez do titânio atrativo na substituição das ligas não nobres.

As ligas de titânio foram utilizadas por muitos anos na indústria aeroespacial e marinha, sendo introduzidas na Odontologia nas últimas décadas (Blackman *et al*., 1991). A liga mais comumente utilizada para esse fim é a liga alfa-beta, Ti-6Al-4V. Suas propriedades físicas e mecânicas são superiores às do Titânio cp (Lampman, 1990; Wang & Fenton, 1996). Essa liga apresenta resistência à flexão (890 MPa) superior quando comparada ao Ti cp (390 MPa), e dureza (350 VHN versus 160 VHN) superior, apresentando-se similar às ligas de Ni-Cr e Co-Cr (Wang & Fenton, 1996), entretanto, apresenta soldabilidade inferior à do Ti cp (Lampman, 1990).

A baixa densidade do titânio associada ao baixo número atômico lhe confere baixo grau de radiopacidade, o que permite a observação radiográfica da qualidade da estrutura fundida (Wang & Boyle, 1993; Zavanelli & Henriques, 2001). Diversos autores relataram ser possível verificar a presença de porosidade no interior de estruturas confeccionadas nesse metal por meio de radiografias periapicais (Wang & Boyle, 1993; Zavanelli *et al.,* 2000; Zavanelli & Henriques, 2001; Zavanelli *et al.,* 2004; Guilherme *et al.*, 2005), entretanto, Botega em 2005 afirmou não ser possível visualizar porosidade interna em espécimes fundidos nesse metal.

Mesmo com tantas características favoráveis, sabe-se que o processo de fundição do titânio é difícil, pois apresenta alto ponto de fusão ($\pm$1700º C) e alta reatividade química com o oxigênio quando aquecido a temperaturas elevadas (acima de 600º C) (Wang & Fenton, 1996). Assim, é necessário fazer uso de equipamento especial, que mantenha atmosfera inerte de gás argônio, impedindo a contaminação do metal (Taira *et al.*, 1989; Craig *et al*., 1993). Além disso, outros cuidados devem ser tomados, tais como união dos condutos de alimentação com ângulos arredondados durante o enceramento, uso de condutos de alimentação largos, além de seleção e manipulação correta do material de revestimento (Wang & Fenton, 1996).

Para que se obtenha sucesso em um tratamento utilizando próteses confeccionadas sobre implantes é necessário que seja feito um planejamento adequado e cauteloso, que sejam tomados os devidos cuidados durante os procedimentos clínicos e laboratoriais, que sejam confeccionadas infra-estruturas metálicas resistentes aos esforços mastigatórios e à corrosão, e que se obtenha a melhor adaptação possível dos pilares, com passividade (Sjögren *et al*., 1988). O assentamento passivo é um dos fatores primordiais para a longevidade da reabilitação com próteses suportadas por implantes. Essas próteses requerem maior precisão na adaptação quando comparadas às sobre dentes naturais, devido à ausência de ligamento periodontal, pois a desadaptação poderia acarretar danos na interface osso/implante (Chai & Chou, 1998; Sahin & Çehreli, 2001).

Os procedimentos clínicos e laboratoriais, mesmo quando realizados de maneira criteriosa, invariavelmente geram distorções na peça finalizada, as quais podem ocorrer devido à técnica, material de moldagem utilizado, obtenção do modelo de gesso, confecção do padrão de cera, procedimentos de fundição e aplicação do revestimento estético sobre a infra-estrutura (Wee *et al*., 1999; Lee *et al*., 2008). E para contornar desvantagens inerentes à obtenção de um monobloco, várias estratégias têm sido propostas visando ao aumento da precisão ou à diminuição de erros inerentes ao processo de confecção da prótese. O corte em segmentos da estrutura em monobloco e a reunião pela técnica da soldagem é uma delas, tornando-se um processo bastante difundido. Quando realizada convencionalmente – mediante o uso de fonte de calor e liga de solda – como para as infra-estruturas em liga de Co-Cr, a técnica aquece demasiadamente a peça protética induzindo alterações dimensionais e modificações de propriedades, incorporando falhas (Henriques *et al*., 1997). Para o titânio e suas ligas, a técnica de união geralmente realizada é a soldagem a “laser”.

A soldagem a laser é considerada um método prático, já que não necessita da inclusão da peça em revestimento, sendo realizada no próprio modelo (Gordon & Smith, 1970; Souza *et al.*, 2000), além de ser um método que acarreta em menor índice de distorções, já que o feixe de laser pode ser concentrado em um ponto muito pequeno, evitando o aquecimento da peça toda, não sendo necessário o uso de outro metal para a realização da soldagem (Tambasco *et al*., 1996; Wang & Chang, 1998).

Características intrínsecas do processo de soldagem podem alterar as propriedades mecânicas do metal na região soldada (Berg *et al*., 1995; Liu *et al.*, 2002; Zavanelli *et al.*, 2004). Gordon & Smith, 1970, iniciaram os primeiros estudos a respeito da soldagem a laser, seguidos por Huling & Clark, 1977, e até hoje esse tipo de soldagem desperta interesse de pesquisadores, que buscam avaliar as conseqüências desse procedimento sobre a qualidade da peça finalizada, e o que isso pode representar na longevidade do tratamento.

Apesar da melhor adaptação aos pilares, a infra-estrutura soldada pode não apresentar a mesma resistência quando comparada a infra-estrutura fundida em monobloco, quando submetida a esforços cíclicos presentes durante o ato da mastigação. Esses esforços estão diretamente ligados ao fenômeno de fadiga, que causa alteração na estrutura do material, sendo permanente, localizada e progressiva, podendo ou não levar à fratura do componente depois de determinado número de ciclos (Vallittu & Luotio, 1996; Henriques *et. al.*, 1997). Chiaverini (1977) relatou que 90% das falhas mecânicas de estruturas metálicas ocorrem devido a esse fenômeno, que está intimamente ligado às características superficiais. Porosidade interna, inclusões, descontinuidades geométricas e irregularidades agem como concentradores de tensão e com isso tendem a iniciar a formação e propagação de trincas (Henriques *et al.,* 1997).

Zavanelli *et al.* em 2004 analisaram a resistência à fadiga-corrosão de espécimes fundidos em liga de Ti-6Al-4V e em Ti cp, imersos em diferentes meios de armazenagem (saliva artificial fluoretada, saliva artificial e sem meio), que simulavam situações rotineiras da cavidade oral. Os autores verificaram que o número de ciclos diminuiu em função dos meios de armazenagem, ou seja, o meio, saliva artificial e saliva artificial fluoretada, promoveram a corrosão dos espécimes diminuindo a resistência à fadiga dos mesmos. Não houve diferença quanto ao tipo de metal utilizado. Após a fratura, os corpos de prova foram soldados a laser, solicitados novamente e a superfície fraturada foi analisada em microscopia eletrônica de varredura (MEV), mostrando a presença de poros nas interfaces soldadas. Assim, puderam concluir, que o procedimento de soldagem reduz a resistência à fadiga do Ti cp e da liga de Ti-6Al-4V.

Baba & Watanabe em 2005 investigaram o efeito da voltagem (V) e do diâmetro do raio (mm) na profundidade de penetração da soldagem a laser em ligas odontológicas (Ti cp, Ti-6Al-4V, Ti-6Al-7Nb, Co-Cr e ouro tipo IV). Dois blocos (3 mm de espessura) de cada metal foram soldados nas seguintes condições: 160-340 V, diâmetro do raio de 0,4-1,6 mm, e duração do pulso de 10 ms. Após a soldagem, os blocos foram separados e a profundidade de penetração da solda foi mensurada. A voltagem e o diâmetro do raio afetaram a profundidade de penetração para todos os metais testados; assim, quando a voltagem aumenta e o diâmetro do raio diminui, aumenta a profundidade de penetração. Dessa maneira, os autores puderam concluir que é importante selecionar condições apropriadas para a soldagem a laser para que se obtenha suficiente profundidade de penetração em função das espessuras soldadas.

Diversos autores estudaram a qualidade da solda a laser realizada em Ti cp e/ou liga de Ti-6Al-4V (Sjögren *et al.*, 1987; Roggensack *et al.*, 1993; Yamagishi *et al.*, 1993; Berg *et al.*, 1995; Wang & Welsch, 1995; Chai & Chou, 1998; Zavanelli *et al.*, 2000; Wiskott *et al.*, 2001; Liu *et al.*, 2002; Hart *et al.*, 2006; Rocha *et al.*, 2006; Watanabe & Topham, 2006); entretanto, na literatura consultada, nenhum autor analisou a qualidade dessa união em diversas situações clínicas simuladas, realizando ensaio de resistência à fadiga.

Dessa maneira, o objetivo desse estudo foi verificar a incidência de porosidade interna nos corpos de prova fundidos em Titânio comercialmente puro em função da variação dos diâmetros dos mesmos; verificar essa incidência no interior das uniões soldadas a laser confeccionadas em estruturas fundidas em Ti cp e usinadas em liga de Ti-6Al-4V, simulando diversas situações clínicas; analisar a resistência à fadiga de corpos de prova soldados a laser em estruturas fundidas em Ti cp, e usinadas em liga de Ti-6Al-4V, simulando diversas situações clínicas; e analisar radiograficamente a qualidade da união soldada e observar o aspecto da superfície de fratura, correlacionando os achados com os ensaios de resistência à fadiga.

Nesse trabalho, a união soldada a laser em Ti cp foi analisada utilizando-se espécimes fundidos, já que na prática clínica, quando infra-estruturas protéticas são confeccionadas por laboratórios de próteses dentais, geralmente elas são fundidas em Ti cp. Todavia, quando se utilizam componentes pré-fabricados ou infra-estruturas usinadas (sistema CAD-CAM), essas são confeccionadas, geralmente, em liga de Ti-6Al-4V, o que motivou a análise de corpos de prova usinados nessa liga.

# 2. CAPÍTULOS

Esta dissertação está baseada na Resolução CCPG/002/06UNICAMP que regulamenta o formato alternativo para teses de Mestrado e Doutorado. Cinco capítulos contendo artigos científicos compõem este estudo, conforme descrito abaixo:

**Capítulo 1.** Inspection of porosity in pure titanium dumbbell rod castings with different diameters

Artigo nas normas do periódico **International Dental Journal**

**Capítulo 2.** Porosity survey of laser-welded joints made with Ti-6Al-4V alloy

Artigo nas normas do periódico **Journal of Oral Rehabilitation**

**Capítulo 3.** Análise radiográfica de uniões soldadas a laser executadas no titânio comercialmente puro fundido, em diversas situações clínicas simuladas

Artigo nas normas do periódico **Ciência Odontológica Brasileira**

**Capítulo 4.** Fatigue strength: Effect of laser-weld joint openings in Ti-6Al-4V structures with several diameters

Artigo nas normas do periódico **The Journal of Prosthetic Dentistry**

**Capítulo 5.** Fatigue performance of joints executed in pure titanium structures with several diameters

Artigo nas normas do periódico **Biomaterials**

# CAPÍTULO 1

## Inspection of porosity in pure titanium dumbbell rod castings with different diameters

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# Inspection of porosity in pure titanium dumbbell rod castings with different diameters

## Abstract

The aim of this study was to evaluate the porosity inspection possibility in pure commercial titanium castings. Sixty dumbbell rods (n=20) with central diameters of 1.5, 2.0 and 3.5 mm ($G_1$, $G_2$ and $G_3$, respectively) were prepared by a lost-wax casting procedure with the Rematitan System. The casting specimens were finished and polished and submitted to radiographic examination (90 KV, 15 mA, 0.6 second and 10 to 13 mm of distance) with periapical film. The radiographies were visually analyzed for the presence of porosity in the entire extension of the dumbbell and just in the central part. Data were submitted to the Chi-Square test (5%). Within the limitations of this study, it was possible to visualize internal porosity in pure titanium castings in most of the specimens (91.7%), particularly in the small diameter specimens.

**Keywords:** Titanium; Casting; Dental Radiography; Dental Implantation; Prosthesis

## Introduction

Bränemark *et al.*, in the early 1950's and 60's, initiated and developed Implantology studies and techniques that allowed the emergence of an alternative to fixed and removable prosthesis rehabilitation prepared traditionally over natural teeth [1,2]. With the success of implants, multiple and single prostheses became more frequent, especially due to the preservation of adjacent healthy dental structures, and complete dentures with increased retention and stability [3].

Initially, prosthetic frameworks were made from precious metals, but due to the high cost, they were replaced by semi-precious metals. However, these metals present some disadvantages, such as low corrosion resistance, insufficient cervical fit and possible allergic reactions to elements such as nickel and beryllium. With the Implantology approach, the use of titanium in framework constructions has been studied, due to the excellent biocompatibility of this metal, as well as its corrosion resistance, desirable physical properties, low cost, low density and low thermal conductibility [4-8]. Its high melting point ($\pm 1700^{o}C$), high reactivity with oxygen, and low density makes conventional centrifugal casting difficult, requiring special equipment that maintains an argon inert atmosphere to prevent the metal contamination [4,5]. However, gas arrestment can lead to the appearance of pores inside the metal structure, resulting in framework failure [9]. Other precautions must also be taken when using this material, such as the use of a large sprue, the union of the sprues in round angle during the waxing process, correct selection and manipulation of the investment material [7].

Titanium's low density allows a routine dental radiography to analyze porosity inside structures [9]. This inspection can be made in metal structures of removable prostheses in order to reject imperfections, or in fixed partial prostheses in use, enabling the visualization of secondary caries [10]. The examination is carried out by exposing structures to radiation of 90 KV, 15 mA, for 0.6 second and with a 10 to 13 mm distance between the radiographic cone and the titanium structure using periapical film [10].

Botega, in 2005 [11], reported that it was not possible to find porosity in specimens melted in pure titanium; other authors found porosity in radiographies after the casting process [12, 13], but not in welded joints [12]. Consequently, the aim of this study was to confirm the efficiency of this radiographic exam and verify the incidence of porosity in melted specimens, correlating the findings with the variation of the diameters at their central segment.

## Material and Methods

Sixty dumbbell shaped rods (Fig. 1) with diameters of 1.5, 2.0 and 3.5 mm in the central segment were made in acrylic resin Duralay II (Reliance Dental Mfg Co, Chicago, USA) on a metal matrix, allowing the formation of three groups (n=20), $G_1$, $G_2$ and $G_3$, respectively. The dumbbell rod dimensions were based on ASTM E8M-04 [14]. The diameters used simulated the following situations: $G_1$, three element fixed prosthesis frameworks; $G_2$, overdenture bars; $G_3$, ten element fixed prosthesis frameworks. The acrylic resin dumbbell rods were visually observed, to evaluate any flaw in the structures and casted in a vacuum injection titanium casting machine (Rematitan System; Dentaurum, Pforzheim, Germany) with commercially pure titanium (CP Ti) [4]. To accomplish this, acrylic resin patterns of each specimen were invested (Rematitan Plus; Dentaurum, Pforzheim, Germany) using a 250g powder and 40 mL liquid ratio and mixed under vacuum, according to the manufacturer's instructions. After setting, invested specimens were heated using a slow heat cycle [15] for wax removal. Following identical manufacturing procedures, the specimens were casted using 36g CP Ti ingots. Molds were immediately immersed in cold running water after casting.

Specimens were divested with the help of a pneumatic hammer (M320 - Flli Manfredi - Sofia - Italy) and airborne particles abraded at a pressure of 80 $lbf/in^2$ with 100 μm aluminum oxide particles [16]. The specimens then were finished and polished with titanium's drills (Rematitan, Dentaurum, Pforzheim, Germany), rubber nº 5001 polisher (Dedeco Dental, New York, USA) and titanium polishing paste (Tiger Brilliant Polier Paste, Dentaurum, Pforzheim, Alemanha). During the finishing process, specimens' diameters were constantly verified with an electronic caliper (Starret, Microtec Instrumentos de Precisão M. E., Sao Paulo, Brazil), assuring accuracy within 0.01 mm [15].

Radiographies of the specimens were taken with radiographic film (Ektaspeed Plus, Eastman Kodak, Rochester, NY) to verify internal defects. The radiographic exam consisted of the exposure of the specimens to radiation (90 KV, 15 mA, 0.6 second and 10 to 13 mm of distance), using a periapical film [10]. The radiographies were visually analyzed for the presence of porosity in along the entire extension of the dumbbell rods and just in the central portion. Data were submitted to the Chi-Square test (5%).

## Results

The radiographic examination, mentioned in the literature, [9, 10] is an efficient evaluation procedure, allowing the visualization of internal porosity in specimens casted in CP Ti (Fig. 2). Table I shows the incidence of internal porosity (%) found in the central sections of the dumbbell rods of all diameters. Regardless of the central diameter, the presence of porosity in this region was found in approximately 20% of the specimens, without differences between diameters ($p = 0.612$).

Table II shows this incidence in the total extension of the specimens, in all groups. The presence of porosity is inherent to the casting process, since it occurs in most of the casting structures, representing 91.7% of the samples in this study. In the 1.5 mm specimens, the presence of radiographic porosity was observed to be more frequent ($p = 0.0005$).

## Discussion

Even though the use of titanium for dental purpose provides reliable results for framework casting, its use presents some disadvantages, including a high melting point ($\pm 1700^{o}C$) and high reactivity with oxygen, requiring an argon inert atmosphere to prevent metal contamination [4,5,7,17].

The casting process, in general, while considered to be technologically dominated, can still result in failures that cause internal defects in the structures obtained; these include internal voids, cracks, external discontinuities and irregularities [13] and, in titanium and its alloys, these defects are more evident due to the casting process and metal physical properties. An argon pressure in the superior chamber can cause gas arrestment; and the low density ($4.2 g/cm^3$) [9] of this metal, makes the flow of melted titanium into the investment mould difficult [5, 18].

In some dental alloys, voids and heterogeneities cannot be observed by visual examinations or by other accessible methods in dentistry. However, due to its low atomic number and, consequently, light specific weight, titanium and its alloys present low radiopacity level, compared to other dental alloys [9, 13], allowing the visualization of internal porosity by radiography [9, 10]. According to the results of this study (Table II), the method described by Zavanelli & Henriques in 2001 [10] efficiently visualizes internal porosity in titanium casted frameworks, since internal porosities were observed in 91.7% of the radiographically-analyzed cast specimens ($p = 0.0005$), usually being observed at the extremity of the dumbbell rods (Table I).

Guilherme *et al*., in 2005 [13], reported this radiographic method to efficiently exclude imperfect specimens. However, after microscopic analysis of the fatigue fractured surface of perfect specimens, they noticed internal porosity on the framework that due to the small magnitude had not been detected by radiographic method.

Botega (2005) [11] reported that it was not possible to visualize internal defects, present in different quantities in specimens, by radiographic analysis. This affirmation contradicts the findings of the present study and those of other studies in the literature [8-10,12,13,19].

As previously reported, the low density of titanium impedes the flow of melted metal into the investment mould [18]. Thus, a protocol must be followed during the investment procedure of the specimens [20] to allow the mould to be completely filled, and to delicately transfer the sprues. The waxed specimens must not be too rough and should have large diameters at the central segment to promote maximum density and avoid minimum porosity [20]. These data explain the finding that the 1.5 mm specimens presented the highest incidence of internal porosity when the entire extension of the dumbbell rods was analyzed. The central segment of the dumbbell rod mould investment worked as a sprue, through which the melted metal drained into the specimen border, where most internal pores were found. However, when the central portion was analyzed, no statistical differences between the diameters were seen.

Within the limitations of this study, radiographic analysis was found to be an efficient method for carrying out internal porosity inspection in structures made of titanium. The clinician should use this method during the manufacture of frameworks before their approval. The incidence of defects is higher when the total extension of the structure is analyzed, especially in thin specimens. Other studies should be performed in order to continue this investigation such as the analysis of internal porosity in welded joints in CP Ti and its alloys, in an attempt to improve framework quality.

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**Table 1.** Internal porosity (%) found in the central section of the dumbbell rods, according to diameter.

| Group | Presence (%) |
|---|---|
| $G_1$ | 20 |
| $G_2$ | 20 |
| $G_3$ | 25 |
| **Total (%)** | 21.7 |

Chi-Square test (p = 0.612)

**Table 2.** Internal porosity (%) found in the total extension of dumbbell rods, according to diameter.

| Group | Presence (%) |
|---|---|
| **$G_1$** | 100 |
| **$G_2$** | 90 |
| **$G_3$** | 85 |
| **Total (%)** | 91.7 |

Chi-Square test ($p = 0.0005$)

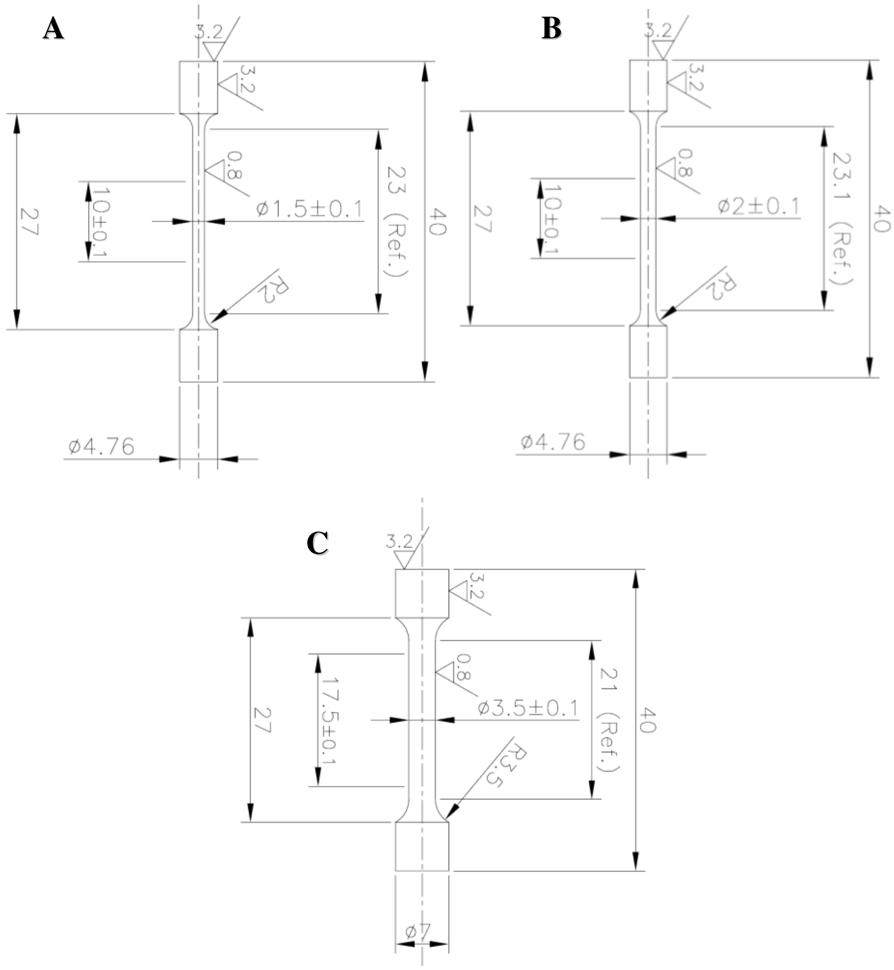


**Figure 1:** Specimen diameters **(A)** 1.5 mm **(B)** 2.0 mm **(C)** 3.5 mm.

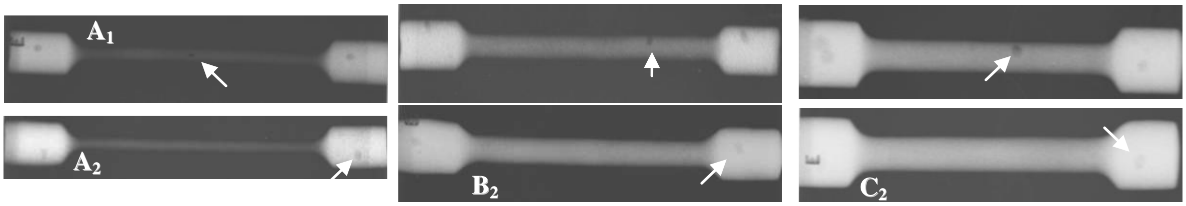


**Figure 2.** Specimen radiographies:

Internal porosity ($A_1$ / $A_2$) 1.5mm ($B_1$ / $B_2$) 2.0mm ($C_1$ / $C_2$) 3.5mm

# CAPÍTULO 2

## Porosity survey of laser-welded joints made with Ti-6Al-4V alloy

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# Porosity survey of laser-welded joints made withTi-6Al-4V alloy


## Abstract

This study was carried out to evaluate the use of radiographic procedures to check the occurrence of pores in laser-welded joints that were made in Ti-6Al-4V structures with several diameters and joint openings. Sixty dumbbells rods with central diameters of 1.5, 2.0 and 3.5 mm were machined from Ti-6Al-4V wrought bars. Specimens were sectioned and then welded using two joint openings (0.0 and 0.6 mm). The combination of the different diameters and joint openings created six groups (n=10). Laser-welding was executed using 360V/8ms (1.5 and 2.0 mm) and 380V/9ms (3.5 mm), with the focus and frequency regulated at zero. The joints were finished, polished and submitted to radiographic examination (90 KV, 15 mA, 0.6 seconds and 10 to 13 mm of distance) with periapical film. The radiographs were visually analyzed for the presence of porosity in the joints. Data were submitted to the Chi-Square test (5%) and internal porosity was visualized in the joints analyzed. For the 1.5 mm specimens, the incidence was higher when the 0.6 mm joint openings were used; conversely for the 3.5 mm specimens, the incidence of internal porosity was lower for the 0.6 mm joint opening.



**Key Words:** Titanium Alloys; Laser-welding; Dental Radiography; Prostheses and Implants; Dental Alloys.

## Introduction

Titanium alloys have been used for some years for the manufacture of aerospace products and in the marine service, but have only recently been introduced for dental applications over the last two decades (1). From an industrial point of view, titanium alloys are attractive due to their low specific gravity, high strength-to-weight ratio, fatigue and corrosion resistance (1, 2) and, importantly in dentistry, their biocompatibility. Titanium alloys possess many of the clinically favored properties of type-III and IV gold dental alloys, but with a lower cost. The Ti-6Al-4V alloy is the most commonly used titanium alloy in dentistry (3).

Passive fit to osseointegrated implants (4) and modifications or repair of fractured titanium alloys frameworks can be achieved with the laser welding procedure (1). Welding is a metallurgical joining process that relies on the fusion of the base metals, with or without metal filler, for the formation of the joint (5-7). Titanium alloys are characteristically difficult to cast and solder due to their high melting points and strong affinity to gases such as oxygen, hydrogen and nitrogen (8, 9). As such, specific equipment that employs an argon shield in the welding chamber is required for soldering titanium alloy frameworks (4, 10-12).

The laser-welding technique has been reported to create a smaller heat-affect zone (HAZ), reduced distortion in the framework and less damage to the veneer coverage. In addition, some studies have demonstrated laser-welded joints to present yield strengths close to those of the base metal under static conditions (3-5). However, several studies investigating the laser welding of titanium and titanium alloys have shown increased hardness in the welded zone and the presence of large pores in the laser-repaired joints (12, 13).

To investigate porosity inside titanium structures, a simple method developed by Wang & Boyle in 1993 (14) may be utilized, whereby the framework is exposed to radiation (90 KV, 25 mA, 30 seconds and at a distance of 10 mm) using an occlusal film. In 2001, Zavanelli & Henriques (15) related a similar method in which titanium was exposed to radiation (90 KV, 15 mA, 0.6 seconds and distance of 10 to 13 mm). The low density (4.2g/cm$^3$) of titanium allows this routine dental radiography to investigate porosity in frameworks, internal defects in specimens to be tested, or secondary caries below crowns made in titanium (14, 15). Using the radiographic method, many authors have observed internal porosity in titanium castings (9, 13), but not in the laser-welded joints executed in titanium and titanium alloy (13).

As such, the aim of this study was to confirm the efficacy of a radiographic method in laser-welded joints made in Ti-6Al-4V alloy specimens, and to evaluate whether different opening joints executed in specimens with different central diameters influence internal porosity occurrence in radiographies.

## Material and Methods

Sixty dumbbell-shaped rods were machined, based on norm ASTM E8M-04 (16) with diameters of 1.5, 2.0 and 3.5 mm in the central segment (Fig. 1). Rods were sectioned in half, perpendicularly to the long axis, and the two sectioned parts were lined up in a metal matrix in order to maintain 0.0 and 0.6 mm opening joints.

The diameters and opening joints were selected to simulate the following situations: 1) Central diameter of 1.5 mm: three element fixed prosthesis frameworks; 2) Central diameter of 2.0 mm: overdenture bars; 3) Central diameter of 3.5 mm: ten element fixed prosthesis frameworks; 4.) 0.0 mm joint opening: precast cut; 5.) 0.6 mm: cut with thin disc.

The combination of the different variables (diameters and joint openings) created six groups (n=10): $G_1$) Central diameter of 1.5 mm and 0.0 mm joint opening; $G_2$) Central diameter of 1.5 mm and 0.6 mm joint opening; $G_3$) Central diameter of 2.0 mm and 0.0 mm joint opening; $G_4$) Central diameter of 2.0 mm and 0.6 mm joint opening; $G_5$) Central diameter of 3.5 mm and 0.0 mm joint opening; and $G_6$) Central diameter of 3.5 mm and 0.6 mm joint opening. The specimens were aligned in the metal matrix and fixed (Fig. 2) with acrylic resin Duralay II (DuraLay, Reliance Dental Mfg Co, Chicago, USA), respecting the joint openings. After the union, the specimens were invested in type IV gypsum, and the resin was removed with a wire cutter after the gypsum crystallization. The metal adjacent to the gap was airborne particles abraded at a pressure of 80 lbf/in$^2$ with 100 μm aluminum oxide particles (17). Two laser-welding points were executed on opposite sides of the specimen to stabilize them. The gypsum was then removed and the welding was completed with a Desktop –F (Dentaurum, Pforzhein, Germany) laser machine, using an energy power of 360V/8ms (1.5 and 2.0 mm specimens) and 380V/9ms (3.5 mm specimens), with the focus and frequency calibrated at zero. The welding process was carried out by a trained and competent professional.

After the welding process, the joints were finished and polished using a nº 5001 rubber polisher (Dedeco Dental, New York, USA) and titanium polishing paste (Tiger Brilliant Polier Paste, Dentaurum, Pforzheim, Germany). During the finishing process, specimens' diameters were constantly verified with an electronic caliper (Starret, Microtec Instrumentos de Precisão M. E., Sao Paulo, Brazil), assuring an accuracy of within 0.01 mm (18).

Radiographs of the joints were taken with radiographic film (Ektaspeed Plus, Eastman Kodak, Rochester, NY, USA) to check for the presence of internal defects. The radiographic examination consisted of the exposure of the specimens to radiation (90 KV, 15 mA and 0.6 seconds, at a distance of 10 to 13 mm) using periapical film (15). The radiographs were visually analyzed for the presence of internal porosity in joints. Data were submitted to the Chi-Square test (5%).

## Results

Table I shows the incidence of internal porosity (%) in the laser-welded joints of the 1.5 mm-diameter specimens. When the joint was made with a joint opening of 0.0 mm, a lower incidence of internal porosity was observed (0%), which differed statistically ($p = 0.0001$) to that of the 0.6 mm joint opening specimens (40%). For the 2.0 mm specimens (Table II), there was no statistical difference between the distances ($p = 0.2008$).

Conversely, statistical difference ($p=0.0061$) was found when the joint openings of the 3.5 mm specimens were compared (Table III). The incidence of porosity was higher (70%) when there was contact between the parts.

Figure 3B shows the internal porosity presented in a 3.5 mm specimen welded with a 0.6 mm joint opening, and the figure 3A, in a 2.0 mm specimen with 0.0 mm of joint opening.

## Discussion

The efficiency of the radiographic method, as proposed by Zavanelli & Henriques, in 2001 (15), to check the presence of internal porosity in titanium frameworks, was confirmed in this study. In this previous study, the authors reported that internal porosity could be visualized in cast frameworks and in cast specimens, allowing faulty structures to be discarded. Furthermore, this method was purported to enable the analysis or observation of secondary caries below installed frameworks. In another study (13), however, the same research group related difficulty in visualizing porosity in laser-welded joints, in contrast to the results of the present study (Fig. 3), which accomplished the observation of internal pores in joints of specimens with central diameters of 1.5 and 2.0 mm. These diameters are smaller than that analyzed by Zavanelli *et al*., in 2004 (13) (2.3 mm).

The lower density of titanium alloys permits their penetration to radiation depths in structures, allowing the observation of porosity (9, 14, 15, 18). The presence of internal porosity in laser-welded joints can occur due to inadequate laser beam penetration and gas seizure, as a consequence of continuous argon spraying throughout the procedure (9, 12, 13, 19). When the penetration depth of the laser beam is low, a greater internal void may be made (20). According to some authors, laser penetration is limited to 1.5 mm of depth (5, 12, 20, 21), which may explain the higher incidence of internal porosity (70%) in 3.5 mm juxtaposed welded specimens (0.0 mm joint openings) in this study.

In this study, the 0.6 mm joint openings reduced the incidence of internal porosity in large specimens (50%), however, in thin specimens (1.5 mm) the higher quantity of metal addition led to an increased incidence of porosity (40%). Generally, welded joints must project in such a way as to deposit very little filler metal to avoid gas arrest and to attenuate remainder distortions (22). This explains the smaller incidence (0%) of internal voids in the 0.0 mm joints of thinner specimens (1.5 mm). However, when the penetration depth of the laser beam is insufficient, as in the 3.5 mm specimen, the 0.6 mm joint opening is recommended.

According to the literature, contact between parts, which is difficult to obtain clinically, is associated with the success of the union (5, 7, 23); however, in the present study, this was not observed for the 3.5 mm specimen. Thus, if welding of larger titanium frameworks is necessary in the clinical practice, the joint parts must not be juxtaposed. For 2.0 mm specimens, there was no statistical difference between the joint openings analyzed ($p = 0.2008$), which clinically, permit to solder with both designs.

Thus, within the limitations of this study, for structures with central diameters of 1.5 mm or less, the laser welded joints must employ juxtaposed sections. In larger specimens, a distance between the joints parts must exist. To improve laser welded joint quality in 3.5 mm specimens, different joint designs should be studied. The “X” design, for example, could circumvent the insufficient laser beam penetration depth. In this design, the center will maintain parts juxtaposed with a thin diameter that will permit deep penetration of the laser beam, the periphery should then be welded starting from the welding center till the surface of the specimen, reducing the quantity of metal filler (22, 24). This design would probably decrease the incidence of internal porosity.

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**Table I.** Presence of internal porosity (%) in the 1.5 mm diameter specimen, as a function of the joint distance.

| Group | Presence (%) |
|---|---|
| **$G_1$** | 0 |
| **$G_2$** | 40 |

Chi-squared test (p = 0.0001).

**Table II.** Presence of internal porosity (%) in the 2.0 mm diameter specimen, as a function of the joint distance.

| Group | Presence (%) |
|---|---|
| $G_3$ | 50 |
| $G_4$ | 60 |

Chi-squared test (p = 0.2008).

**Table III.** Presence of internal porosity (%) in the 3.5 mm diameter specimen, as a function of the joint distance.

| Group | Presence (%) |
|---|---|
| **$G_5$** | 70 |
| **$G_6$** | 50 |

Chi-squared test (p = 0.0061).

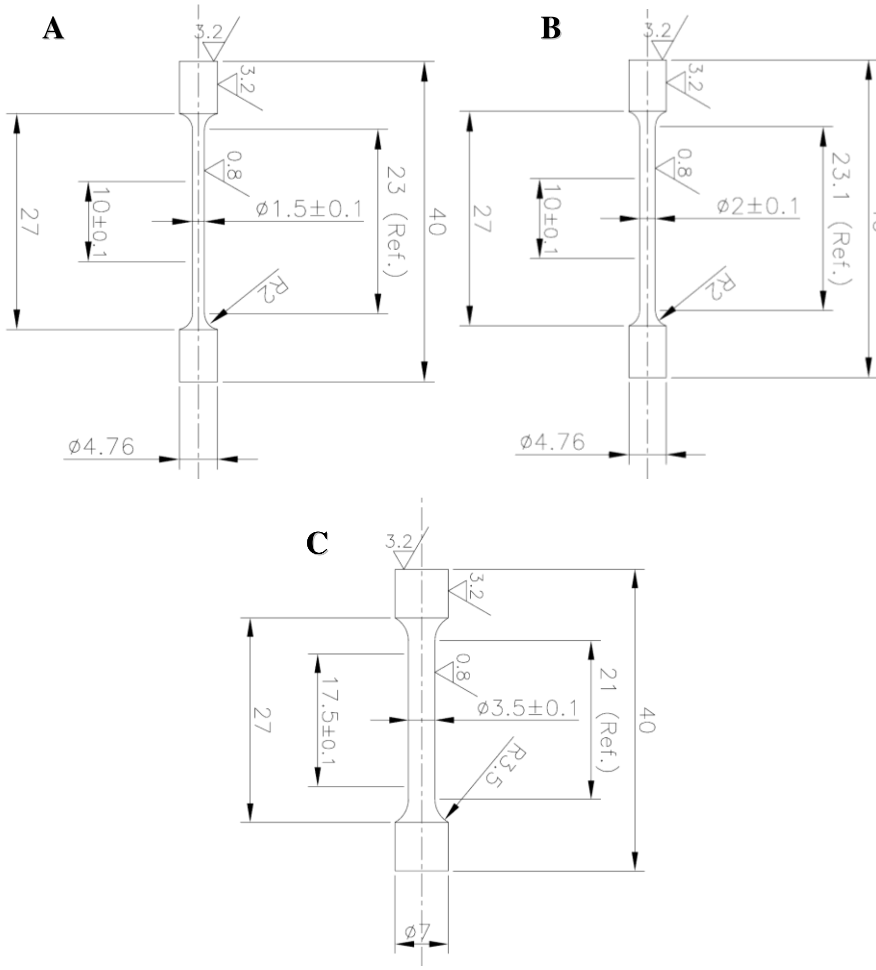


**Figure 1:** Test specimen **(A)** Diameter of 1.5 mm **(B)** Diameter of 2.0 mm **(C)** Diameter of 3.5 mm.

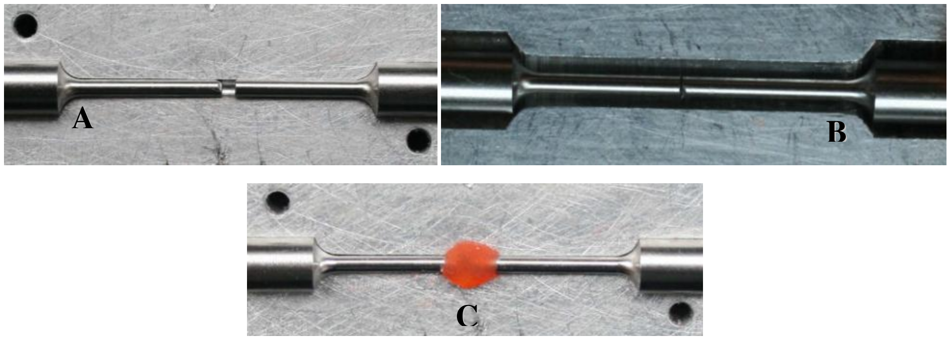


**Figure 2:** Test specimens: **A.** Joint opening of 0.6 mm **/ B.** Joint opening of 0.0 mm **/ C.** Joint with acrylic resin.

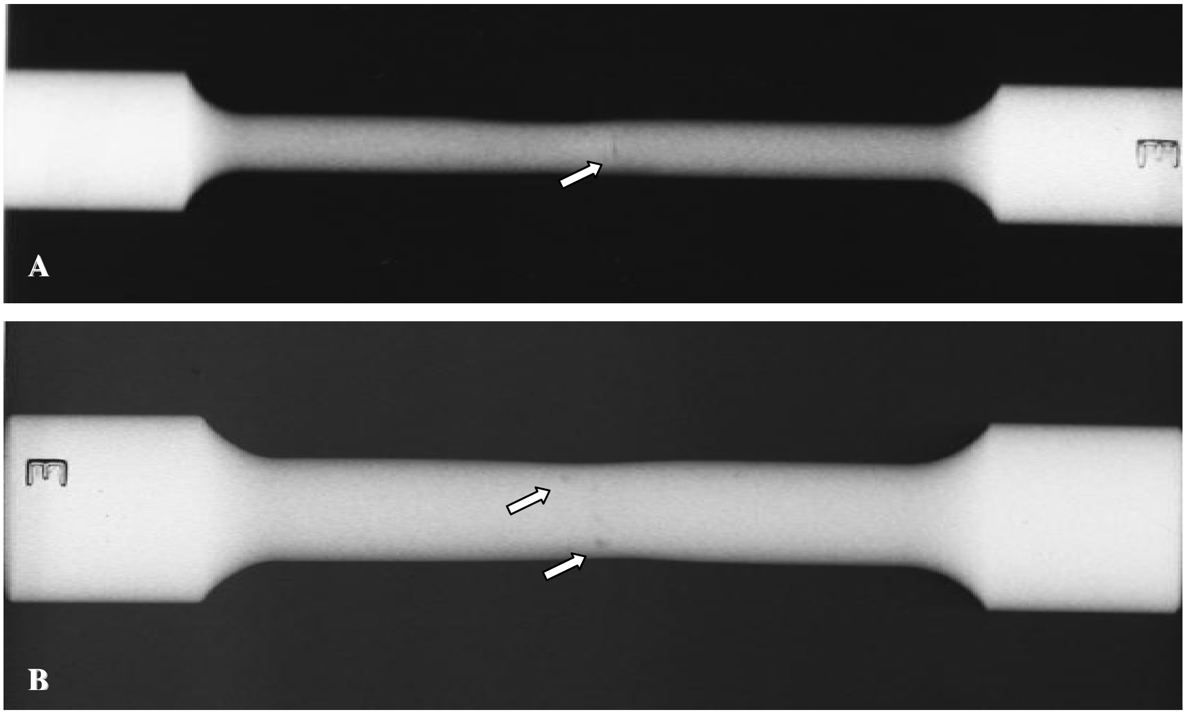


**Figure 3:** Radiographic evidence of the presence of porosity (arrows), in 2.0 mm, 0.0 mm distance **(A)** and 3.5 mm, 0.6 mm distance **(B)** test specimens.

# CAPÍTULO 3

## Análise radiográfica de uniões soldadas a laser executadas no titânio comercialmente puro fundido, em diversas situações clínicas simuladas


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# Análise radiográfica de uniões soldadas a laser executadas no titânio comercialmente puro fundido, em diversas situações clínicas simuladas

## Radiographic analyzes in casting titanium laser-joints in diverse clinical situations


## Resumo

Esse estudo foi conduzido para avaliar a possibilidade de visualização de porosidade interna em radiografias periapicais de uniões soldadas a laser, confeccionadas em estruturas de titânio cp, em diferentes situações de soldagem. Foram confeccionados halteres em resina acrílica, com diâmetros centrais de 1,5; 2,0; e 3,5 mm, por meio de uma matriz metálica bipartida. Os halteres em resina foram fundidos em Ti cp e após acabamento e polimento, seccionados em duas partes iguais. As partes foram alinhadas e fixadas de tal forma que as distâncias entre elas fossem 0,0 e 0,6 mm. A combinação entre as variáveis (distância de soldagem e diâmetro dos halteres) gerou seis grupos (n=10). A soldagem a laser foi realizada com as seguintes especificações: 360V/8ms (1,5 e 2,0 mm) e 380V/9ms (3,5 mm), com foco e freqüência regulados em zero, em um aparelho de soldagem a laser Desktop-F. As uniões obtidas receberam acabamento, polimento e foram submetidas à análise radiográfica com exposição à radiação (90 KV, 15 mA, 0,6 seg e 10 a 13 mm de distância) utilizando filme periapical. As radiografias foram analisadas visualmente quanto à presença de porosidade nas uniões soldadas, e os dados obtidos, submetidos ao teste Qui-Quadrado (5%). Com isso, verificou-se ser possível visualizar porosidade interna nessas uniões. Em espécimes de menores diâmetros, 1,5 e 2,0 mm, a incidência é maior quando a distância é 0,6 mm. Entretanto, em espécimes de 3,5 mm, a incidência é alta para ambas as uniões, não diferindo estatisticamente entre si.



**Palavras Chave:** Titânio; Fundição Odontológica; Soldagem a Laser; Radiografia Dental.


## Introdução

Com o advento da implantodontia (décadas de 50 e 60) o titânio, metal utilizado por muitos anos na indústria aeroespacial e marinha, passou a ser utilizado na Odontologia. Inicialmente, esse material foi empregado na confecção de implantes osseointegráveis, devido a sua biocompatibilidade e capacidade de osseointegração [4]. As próteses suportadas por esses implantes, eram confeccionadas em metais nobres. Devido ao alto custo dos mesmos, passaram a ser substituídas por metais não nobres. Esses metais, por sua vez, apresentavam algumas desvantagens, tais como baixa resistência à corrosão, insuficiente adaptação cervical e possíveis reações alérgicas a elementos como níquel e berílio [8, 22]. Diante desses problemas, iniciaram-se estudos a cerca do uso do titânio também na confecção de infra-estruturas protéticas.

O titânio é atrativo devido à combinação de propriedades desejáveis como baixa densidade, biocompatibilidade, baixo custo, baixa condutibilidade térmica, alta resistência mecânica e à corrosão [5, 9, 14, 18, 22]. Muitas dessas propriedades comparam-se às das ligas de ouro tipo III e IV

[27]. Entretanto, esse metal apresenta alto ponto de fusão (±1700º C) e elevada reatividade química com o oxigênio e nitrogênio do ar quando aquecido a temperaturas elevadas (acima de 600º C), necessitando assim da proteção de atmosfera inerte de gás argônio nos processos de fundição e soldagem [14, 18, 22]. Além disso, apresenta baixo número atômico, que associado à baixa densidade do mesmo, confere-lhe baixo grau de radiopacidade, sendo passível de observação radiográfica [21]. Diversos autores relataram ser possível verificar a presença de poros no interior de estruturas fundidas nesse metal por meio de radiografias periapicais [6, 21, 25-27], entretanto, alguns deles relataram não ser possível realizar essa análise em uniões soldadas a laser em estruturas de titânio e liga de Ti-6Al-4V [27].

Para obter sucesso nos tratamentos utilizando próteses implantossuportadas, faz-se necessário o planejamento cauteloso, tomando-se cuidado durante os procedimentos clínicos e laboratoriais. As infra-estruturas metálicas devem resistir aos esforços mastigatórios e à corrosão, e devem ser assentadas com passividade aos pilares [17]. Devido à ausência de ligamento periodontal nos implantes, a adaptação dessas infra-estruturas devem ser superiores às confeccionadas sobre dentes naturais [5, 16]. Contudo, muitas vezes, os procedimentos clínicos e laboratoriais, mesmo quando realizados de maneira criteriosa, geram distorções na peça finalizada [10, 24]. Nesses casos, é necessário seccionar a peça, para soldá-la após novo relacionamento [4]. No caso do titânio, a técnica de soldagem a laser é a mais empregada [5, 15, 17, 19].

A soldagem a laser tem demonstrado pequena zona afetada pelo calor (ZAC), reduzida distorção causada pela soldagem, pequeno dano ao revestimento estético da prótese, e resistência equivalente à do metal base sob condições estáticas [5, 17, 19]. Entretanto, percebeu-se aumento da dureza na zona soldada e presença de porosidade no interior das uniões [15, 27], que podem tornar as infra-estruturas soldadas menos resistentes quando comparadas às não soldadas.

Diante do relatado, esse estudo foi conduzido a fim de analisar a eficiência do método radiográfico na visualização de poros presentes no interior das uniões soldadas a laser no Ti cp, e avaliar radiograficamente a incidência de porosidade interna diante das variações de distâncias de soldagem e diâmetros das estruturas.

## Material e Métodos

Foram confeccionados padrões em resina acrílica Duralay II (DuraLay, Reliance Dental Mfg Co, Chicago, USA), com formato semelhante a um halter (Fig. 1), baseado na norma ASTM E8M-04 [1], a partir de matrizes metálicas bipartidas. Os padrões encerados foram observados visualmente procurando obtê-los uniformes e livres de falhas. Esses, posteriormente, foram adaptados a condutos de alimentação laterais de 4 mm de diâmetro, e a cada padrão, dois condutos de alimentação adicionais foram adaptados aos condutos laterais (5 mm), evitando-se a formação de ângulos vivos nas intersecções que poderiam dificultar a injeção da liga fundida no molde de revestimento. Em seguida, os condutos de alimentação foram unidos à base cônica do anel inclusor de silicone (Anel de Silicone, Dentaurum J.P. Winkelstroeter KG, Pforzheim, Alemanha). O revestimento (Rematitan Plus, Dentaurum, Pforzheim, Alemanha) foi proporcionado de acordo com as instruções do fabricante (40 mL de líquido específico e 250 g de pó) e espatulado mecanicamente a vácuo por 60 segundos em um espatulador elétrico (Multivac 4, Degussa-Hüls, Hanau, Alemanha). Após a manipulação, a massa foi vazada sob vibração e deixada em temperatura ambiente até o início da reação de cristalização, momento em que o anel foi removido. Após 40 minutos do início da manipulação do revestimento e previamente ao processo de fundição, o bloco cristalizado foi colocado em forno elétrico de aquecimento (EDGCON 5P, Equipamentos e Controles Ltda., São Carlos, Brasil), previamente programado, segundo recomendações do fabricante [25]. Transcorrido o período de aquecimento, os corpos de prova foram fundidos em titânio comercialmente puro (Tritan, Dentaurum J.P. Winkelstroeter KG, Inspringen, Alemanha) em máquina de fundição a vácuo, equipada com arco voltaico (Rematitan, Dentaurum, Pforzheim, Alemanha).

Após a fundição, o revestimento foi imediatamente esfriado em água, por recomendação do fabricante, para evitar contaminação. Em seguida, foi fraturado manualmente e o conjunto metálico removido. Os corpos de prova foram desincluídos do revestimento com auxílio de um martelete pneumático (M320, Flli Manfredi, Sofia, Itália) e jateados com micro esferas de vidro em jateador elétrico (Oxyker Dry, Flli Manfredi, Sofia, Itália). Em seguida, os mesmos receberam acabamento e polimento manual com brocas apropriadas para titânio (Rematitan, Dentaurum, Pfrzheim, Alemanha), borrachas para polimento nº 5001 (Dedeco dental, New York, USA) e pedra para polimento em titânio (Tiger Brillant Polier Paste, Dentaurum, Pforzheim, Alemanha), tendo seus diâmetros constantemente aferidos com paquímetro digital com precisão de 0,01 mm (Starret, Microtec Instrumentos de Precisão M. E., São Paulo, SP). Os procedimentos de fundição dos corpos de prova foram realizados por um técnico experiente e capacitado a fim de simular a prática clínica.

Os halteres fundidos foram submetidos à análise radiográfica para inspeção de porosidade interna. A tomada radiográfica constituiu na exposição do corpo de prova à radiação (90 KV, 15 mA, 0,6 seg e 10 a 13 mm de distância) utilizando filme periapical [26]. Os corpos de prova que apresentaram vazios internos na porção central dos halteres, observados pelo método radiográfico, foram desprezados.

Sessenta corpos de prova fundidos (vinte de cada diâmetro) foram então seccionados na porção central, em função dos seus longos eixos e as partes a serem soldadas, realinhadas na matriz metálica, de tal forma que as distâncias entre elas fossem de 0,0 ou 0,6 mm. Foram selecionados três diâmetros e duas distâncias de soldagem para simular as seguintes situações clínicas: 1. Diâmetro de 1,5 mm: união de infra-estruturas de prótese fixa; 2. Diâmetro de 2,0 mm: união de barra para overdenture; 3. Diâmetro de 3,5 mm: união de infra-estrutura de prótese total fixa implantossuportada; 4. Distância de 0,0 mm: corte pré-fundição; 5. Distância de 0,6 mm: corte com disco fino.

A combinação entre as variáveis (distância e diâmetro) gerou seis grupos (n=10). Os espécimes alinhados na matriz metálica foram fixados, respeitando-se as distâncias pré-definidas, utilizando-se resina acrílica Duralay II (DuraLay, Reliance Dental Mfg Co, Chicago, USA). Após a união, as extremidades dos halteres foram incluídas em bloco de gesso pedra tipo IV. Terminada a cristalização do gesso, a resina foi removida com auxílio de alicate de corte, e o metal adjacente à fenda jateado com óxido de alumínio de granulação 100 $\mu$m e pressão de 5,6 kgf/cm$^2$. Após o jateamento, foi realizada a soldagem em um dos lados da amostra e em seguida no outro, para fixação prévia. O gesso foi removido e a soldagem completada em toda a volta da amostra, através da irradiação de múltiplos pulsos sobrepostos, com energia de 360V/8ms (amostras de 1,5 e 2,0 mm) e 380V/9ms (amostras de 3,5mm), com foco e freqüência regulados em zero, em um aparelho de soldagem a laser Desktop -F (Dentaurum, Pforzhein, Alemanha). A soldagem foi realizada por um profissional treinado e capacitado.

As uniões soldadas receberam acabamento e polimento da mesma maneira que os halteres, após a fundição, e em seguida, foram submetidas à mesma análise radiográfica [26]. As radiografias foram analisadas visualmente quanto à presença de porosidade e os dados obtidos agrupados de acordo com o diâmetro dos halteres e submetidos ao teste Qui-Quadrado (5%).

## Resultados

A tabela 1 mostra a incidência de porosidade interna (%) nas uniões soldadas a laser em halteres de 1,5 mm de secção transversal, em função das distâncias de soldagem. Percebe-se que quando a união é realizada com justaposição das partes, a incidência de porosidade é menor (0%), quando comparada a distância pós corte com disco fino (30%). Pode-se dizer o mesmo para os corpos de 2,0 mm de secção transversal (Tabela 2), entretanto, com incidência de porosidade superior a dos halteres de 1,5 mm. Para a justaposição das partes, os halteres de 2,0 mm apresentaram incidência de porosidade de 40%, e para a distância pós corte com disco fino, 60% (p = 0,0077).

Em contrapartida, quando são analisadas as uniões executadas nos halteres de 3,5 mm de diâmetro (Tabela 3), a incidência de porosidade também é superior a dos halteres de 1,5 mm, não havendo diferença estatística entre as distâncias de soldagem (p = 0,1821).

# Discussão

Esse estudo confirmou a eficiência do método radiográfico sugerido por Zavanelli *et al.*, em 2001 [26]. Entretanto, discordou de Zavanelli *et al.*, em 2004 [27], que relataram não ser possível visualizar poros em uniões soldadas a laser em estruturas de Ti cp e ligas de Ti-6Al-4V, por meio desse método radiográfico. Provavelmente, as porosidades não foram visualizadas por àqueles autores devido à baixa incidência de presença das mesmas, o que provavelmente relaciona-se à união de halteres de 2,3 mm de diâmetro de secção transversal com justaposição das partes. Diante dos resultados desse estudo, pode-se afirmar que nas uniões soldadas a laser essa análise também é efetiva (Figura 2). A baixa densidade do titânio permitiu a penetração da radiação nas estruturas analisadas, possibilitando a visualização desses poros [21, 26].

O aparecimento de vazios no interior das uniões soldadas a laser se dá, principalmente, devido à insuficiente penetração do feixe de laser e à inclusão de gás argônio [3, 15, 27]. A presença desse gás no procedimento de soldagem a laser é necessária para minimizar a contaminação do titânio com o oxigênio e nitrogênio do ar, pois mantêm a atmosfera inerte [3, 27]. Em uniões aonde há maior necessidade de preenchimento dos espaços utilizando-se maior quantidade de metal de adição (distâncias 0,6 mm), independentemente do diâmetro do corpo de prova a possibilidade de aprisionamento de gás é maior. Isso explicaria a maior incidência de porosidade interna nos halteres de 1,5 e 2,0 mm de diâmetro com 0,6 mm de distância de soldagem (30% e 60%, respectivamente), quando comparados aos espécimes com justaposição das partes. Nota-se que a incidência é menor nos corpos de prova de 1,5 mm de diâmetro, visto que a fenda gerada com o espaçamento é menor, devido ao diâmetro mais delgado, necessitando de menor quantidade de metal de adição para preenchê-la, e diminuindo a possibilidade de aprisionamento de gás.

A respeito da insuficiente penetração do feixe de laser, quanto menor é a profundidade alcançada por esse feixe, maior é a quantidade de vazios internos [2]. Segundo diversos autores, essa penetração é limitada a 1,5 mm de profundidade [2, 12, 15, 19], o que explica a elevada incidência de porosidade interna (70%) nos espécimes de 3,5 mm de diâmetro soldados com a justaposição das partes (distância 0,0 mm). Para esses corpos de prova de maior dimensão da secção transversal, não há diferença estatística entre as aberturas das juntas ($p = 0,1821$), visto que em ambas as situações há grande possibilidade de ocorrer formação de poros nas uniões, ou seja, ou se aprisiona gás com facilidade (0,6 mm), ou há penetração insuficiente do feixe de laser na união (0,0 mm).

Em relação aos parâmetros de soldagem utilizados nesse estudo, pode-se afirmar diante dos resultados obtidos, que não foram excessivos. Foram padronizados em função dos diâmetros dos corpos de prova, por um profissional experiente e capacitado, associando-se a experiência do mesmo, aos relatos da literatura. É importante salientar que, apesar da existência de inúmeros trabalhos na literatura a cerca da soldagem a laser [2, 5, 11, 12, 23], ainda não existe um protocolo de soldagem estabelecido.

A potência do laser utilizada durante o processo de soldagem é regulada por dois parâmetros: voltagem e duração do pulso [5]. A voltagem controla a energia de soldagem e relaciona-se diretamente à profundidade de penetração do laser; ou seja, conforme aumenta a voltagem, aumenta também a profundidade de penetração do raio laser [2, 11]. A duração do pulso determina o diâmetro do feixe de laser, quanto maior a duração do pulso, maior o diâmetro do feixe. Assim, quanto maior a voltagem e menor o diâmetro do laser, maior a penetração [2, 5]. Quando a potência é excessiva, e a energia do laser fornecida é prolongada, a temperatura de fusão do metal soldado excede o ponto de ebulição desse metal e causa evaporação do mesmo [2]. O aumento do volume de metal evaporado aumenta a pressão da região soldada, e agita o metal fundido adjacente, formando uma cavidade denominada de “buraco de fechadura” [2, 20], que acarreta na presença de porosidade e irregularidade da união. Nesse estudo, utilizou-se grande potência, quando se compara à excelente determinada por Chai & Chou em 1998 [5]. Entretanto, pode-se dizer que essa potência não foi excessiva, e não foi capaz de causar o dano interno descrito anteriormente, possível de ser visto na radiografia, já que a incidência de porosidade interna para os corpos de prova de 1,5 mm de diâmetro com distância 0,0 mm foi 0%.

Segundo a literatura, o contato entre as partes, difícil de se obter clinicamente, está associado ao sucesso da união [14, 19, 23], o que não correspondeu à verdade para os corpos de prova de 3,5 mm de diâmetro nesse estudo. Assim, os resultados desse estudo permitiram afirmar que na execução de juntas soldadas a laser deve-se depositar o mínimo possível de material de preenchimento, para evitar aprisionamento de gases e atenuar distorções residuais, o que consentiu com Okumura & Taniguchi, em 1982 [13]. Isso explica a menor incidência (0%) de porosidades em espécimes de menor diâmetro (1,5 mm) com distância de união de 0,0 mm. Quando a penetração é insuficiente como nos corpos de prova de 3,5 mm, talvez a projeção de diferentes designs de união, como o design em “X” solucionaria essa elevada incidência [13, 28]. Esse design permite que a soldagem seja iniciada a partir do centro da junta, com justaposição de partes delgadas, sem haver insuficiente penetração do raio laser, e que a periferia, conseqüentemente, seja soldada fazendo-se uso de menor quantidade de metal de adição, quando comparada à quantidade utilizada nas uniões com design em “I” [28], utilizado nesse estudo, após corte com disco fino.

Sabe-se que se a união soldada apresentar trincas, entalhes, poros ou irregularidades, se torna mais susceptível a falhas, já que esses fatores agem como pontos de concentração de tensões [12] e tendem a agir como iniciadores e propagadores de trincas [7]. Esse estudo foi conduzido, portanto, para pesquisar a possibilidade de visualização dessas irregularidades, que podem acarretar em falhas, por meio de um método radiográfico de fácil execução na clínica odontológica. A afirmação de que realmente, há possibilidade de visualizar porosidade interna na união soldada, auxilia na aprovação da prótese soldada a ser instalada. Entretanto, é importante lembrar que não foi feita a quantificação desses poros presentes nas radiografias, nem quanto ao número, e nem quanto ao tamanho dos mesmos, o que provavelmente influenciaria na resistência da união soldada.

## Conclusão

Assim, diante das limitações desse estudo, pode-se concluir que é possível inspecionar radiograficamente porosidade interna em uniões soldadas a laser executadas em Ti cp; e que em corpos de prova de menores diâmetros deve-se realizar, sempre que possível, a soldagem com a justaposição das partes, sendo ambos os designs ruins para a união de espécimes mais espessos.


## Abstract

This study was conducted to evaluate the possibility of internal porosity analysis in periapical radiographies of laser joints executed in cp titanium structures, in several situations. Sixty acrylic dumbbells rods with 1.5, 2.0 and 3.5 mm central diameter were made using a metal matrix. The acrylic specimens were casted in Ti cp and after finishing and polishing, they were sectioned in two halves. The parts were aligned and fixed according two welding distances (0.0 and 0.6 mm). The combination among diameter and welding distance created six groups (n = 10). The laser-welding was executed as follows: 360V/8ms (1.5 and 2.0 mm) and 380V/9ms (3.5 mm) with focus and frequency regulated in zero, in laser welding machine Desktop-F. The achieved joints were finished, polished and submitted to radiographic examination (90 KV, 15 mA, 0.6 second and 10 to 13 mm of distance) with periapical film. The radiographs were visually analyzed for the presence of internal porosity inside the joints. The data was submitted at Chi-Square test (5%). Herewith, it was possible to visualize internal porosity in the analyzed joints. In thin specimens, 1.5 and 2.0 mm, the porosity incidence is higher when the joint distance is 0.6 mm. However, in 3.5 mm specimens, the incidence is high for both joint openings, without statistical difference.



**Key Words:** Titanium; Dental Casting; Laser-welding; Dental Radiography.

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**Tabela 1.** Incidência de porosidade interna (%) na união de halteres de 1,5 mm de diâmetro, em função das distâncias de soldagem.

| Distância (mm) | Presença (%) |
|---|---|
| **0,0** | 0 |
| **0,6** | 30 |

Teste Qui-Quadrado (p = 0,0001).

**Tabela 2.** Incidência de porosidade interna (%) na união de halteres de 2,0 mm de diâmetro, em função das distâncias de soldagem.

| Distância (mm) | Presença (%) |
|---|---|
| **0,0** | 40 |
| **0,6** | 60 |

Teste Qui-Quadrado (p = 0,0072).

**Tabela 3.** Incidência de porosidade interna (%) na união de halteres de 3,5 mm de diâmetro, em função das distâncias de soldagem.

| Distância (mm) | Presença (%) |
|---|---|
| **0,0** | 70 |
| **0,6** | 60 |

Teste Qui-Quadrado (p = 0,1821).

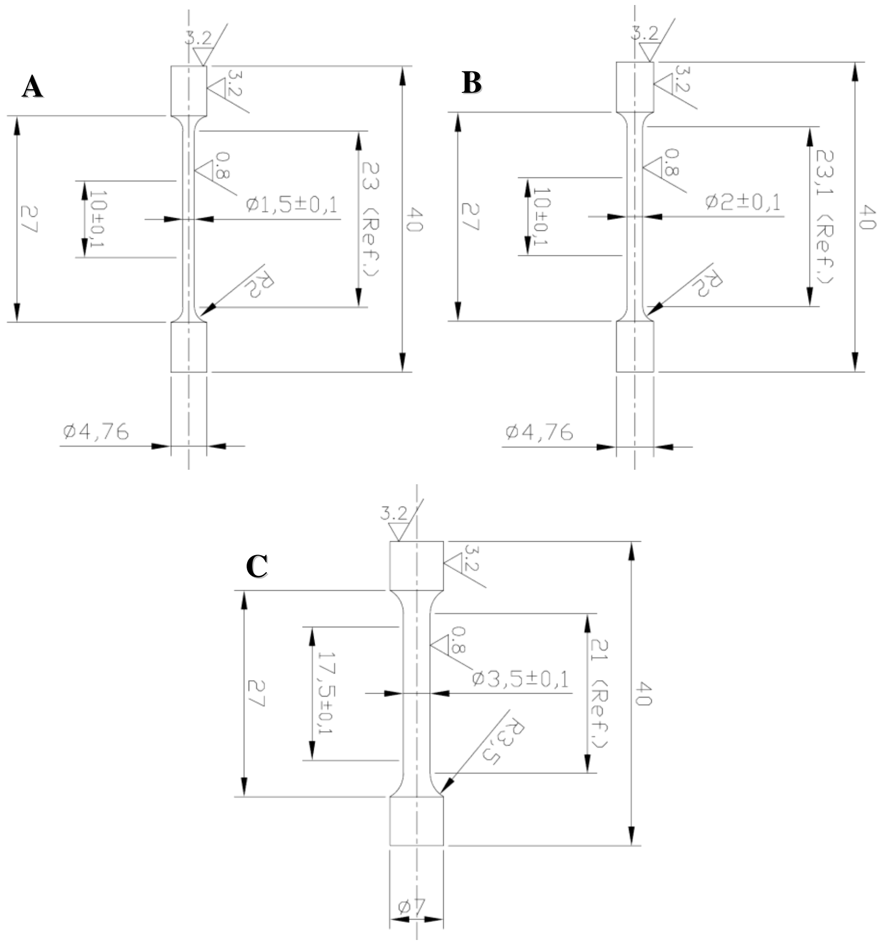


**Figura 1:** Corpo de prova de **(A)** 1,5 mm de diâmetro **(B)** 2,0 mm de diâmetro **(C)** 3,5 mm de diâmetro.

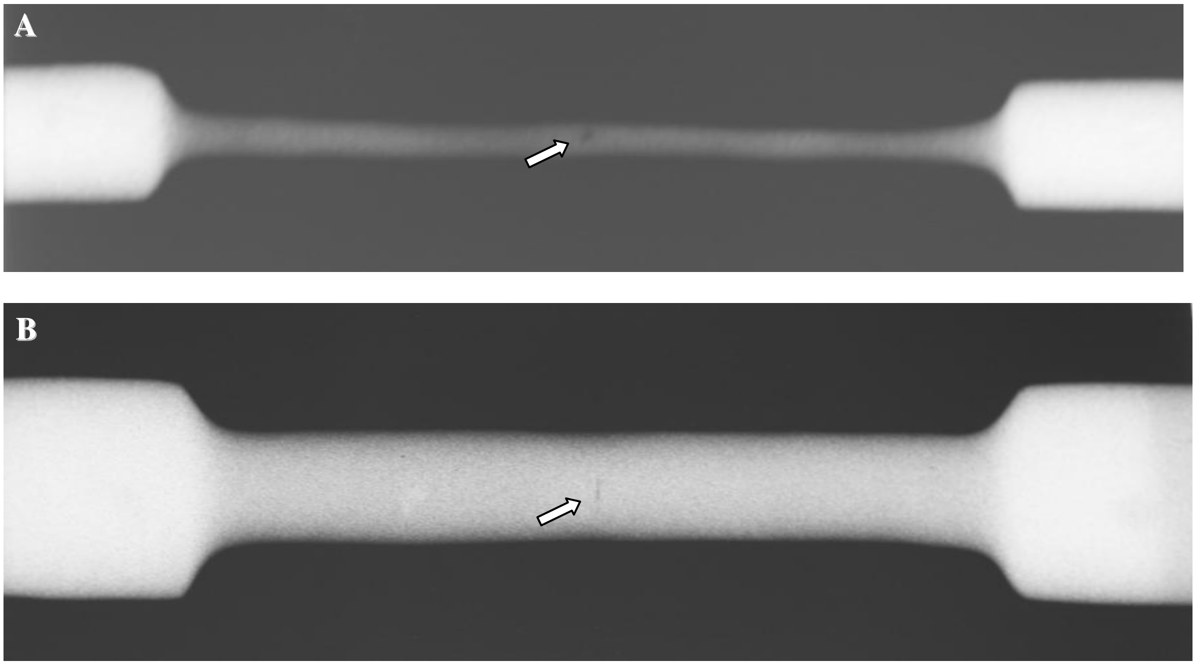

**Figura 2.:** Radiografias evidenciando a presença de porosidade, nas uniões: **(A)** diâmetro de 1,5 mm e distância 0,6 mm; **(B)** Diâmetro de 3,5 mm e distância 0,0mm.

# CAPÍTULO 4

## Fatigue strength: Effect of laser-weld joint openings in Ti-6Al-4V structures with several diameters


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## Fatigue strength: Effect of laser-weld joint openings in Ti-6Al-4V structures with several diameters


## Abstract

**Statement of problem.** Prostheses are affected by fatigue due to wear from the masticatory system.

**Purpose.** This study was conducted to evaluate the fatigue strength of Ti-6Al-4V laser-welded joints with several diameters and joint openings.

**Material and methods.** Sixty dumbbell rods were machined in Ti-6Al-4V alloy with central diameters of 1.5, 2.0 and 3.5 mm. The specimens were sectioned and then welded using two joint openings (0.0 and 0.6 mm). The combination among variables created six groups, which when associated with the intact groups made a total of nine groups (n=10). Laser welding was executed as follows: 360V/8ms (1.5 and 2.0 mm) and 380V/9ms (3.5 mm) with focus and frequency regulated to zero. The joints were finished, polished and submitted to radiographic examination to visually analyze the presence of porosity in the dumbbells joints. The specimens were then submitted to a mechanical cyclic test, and the number of cycles until failure was recorded. The fracture surface was examined with a scanning electron microscope (SEM).

**Results.** Kruskal-Wallis and Dunn test (5%) indicated that the number of cycles required for fracture was lower for all the diameters with joint openings of 0.6 mm, and for 3.5 mm diameter for the 0.0 mm joint openings. The Spearman correlation coefficient (5%) indicated that there was a negative correlation between number of cycles and presence of porosity.

**CLINICAL IMPLICATIONS**

For Ti-6Al-4V frameworks with thin diameters, laser welding is better when structures are juxtaposed. This study demonstrated the increased risk of cracking due to internal voids, as observed by radiographic examination.

## Introduction

Titanium alloy products are primarily used, from an industrial point of view, due to their exceptional fatigue and corrosion resistance and their useful combination of low density and high strength [1-3]. These characteristics are desirable in dentistry; however interest is more sharply focused on biocompatibility [1]. Titanium alloys are cheaper than types III and IV gold dental alloys and possesses a number of clinically favorable properties [1]. Some characteristics of titanium are superior to those of base metals and equal or better than gold alloy type III [1], such as ultimate tensile strength, Vickers hardness, yield strength, Young's modulus, and weight [3,4]. Several titanium alloys are used in dentistry; Ti-6Al-4V is the most used alloy due to its resistance and high performance [2-5].

Implant prostheses require more accurate fabrication criteria than natural teeth prostheses because of the lack of periodontal tissues that compensate for minor relationship errors [5]. There are unavoidable errors in impression procedures [6,7] and/or cast distortion for frameworks that have to be corrected; this correction can be achieved by employing the laser welding procedure [1,8]. Welding is a metallurgical joining process that relies on fusion of base metals with, or without, a filler alloy to form a joint [9-11]. Titanium alloys are characteristically difficult to cast and solder due to the high melting point of this metal and its strong affinity to gases such as oxygen, hydrogen and nitrogen [12,13]. Therefore, use of a special machine that employs argon shielding in the welding chamber is necessary to solder titanium alloy frameworks [8,14-16].

The laser-welding technique has been related to demonstrate a smaller heat-affect zone (HAZ), reduced joining distortions, lower damage to veneering coverage and close yield strength to the base metal under static conditions [5,8,9]. However, several reports on laser welding of titanium and titanium alloys have shown increased hardness in the welded zone and the presence of large pores in the laser-repaired joints [16,17].

Fatigue, which is the process of progressive localized permanent structural change occurring in a material subjected to cyclic loading, is responsible for 90% of all service failures due to mechanical causes [4]. This process is usually initiated by stress raisers such as voids, inclusions, notches, surface roughness modifiers and metallurgical variables. Hence, despite a better fit, the laser-welded frameworks must not present the same fatigue strength as compared to intact structures.

Literature on the laser-welding process is scarce, particularly with regard to the strength of the joint in several situations. Hence, the aim of this study was to evaluate the fatigue strength of Ti-6Al-4V laser-welded joints with several diameters and joint openings and correlate the results with the presence of internal voids observed in the radiographic analyses.

## Material and Methods

Ninety dumbbell shaped rods, with diameters of 1.5, 2.0 and 3.5 mm in the central segment, were machined, based on norm ASTM E8M-04 [18]. Sixty of these rods were sectioned in half, perpendicularly to the long axis, and the jointed portions were lined up in a metal matrix in order to maintain distances of 0.0 and 0.6 mm between them. The aligned specimens were fixed with acrylic resin Duralay II (DuraLay, Reliance Dental Mfg Co, Chicago, USA), respecting the welded distances (0.0 and 0.6 mm). After the union, the specimens were invested in type IV gypsum and after gypsum crystallization the resin was removed with a wire cutter. The metal adjacent to the gap was airborne particles abraded at a pressure of 80 lbf/in$^2$ [19] with 100 µm aluminum oxide particles and the joints were welded on opposite sides of the specimen to stabilize them. The gypsum was then removed and welding was carried out using energy of 360V/8ms (1.5 and 2.0 mm specimens) and 380V/9ms (3.5 mm specimens), with the focus and frequency calibrated at zero, with a Desktop –F (Dentaurum, Pforzhein, Germany) laser machine. The welding process was performed by a trained and competent professional.

Three diameters and two joint distances were used to simulate the following situations: 1.) 1.5 mm of central diameter, three elements fixed prosthesis frameworks; 2.) 2.0 mm of central diameter, overdenture bars; 3.) 3.5 mm of central diameter, ten element fixed prosthesis frameworks; 4.) 0.0 mm joint opening, precast cut; 5.) 0.6 mm joint opening, cut with a thin disc. The combination between the variables created a total of six groups (n=10), which together with the controls groups (intact) made a total of 9 groups.

After the welding process, the joints were finished and polished with a rubber nº 5001 polisher (Dedeco Dental, New York, USA) and titanium polishing paste (Tiger Brilliant Polier Paste, Dentaurum, Pforzheim, Alemanha). During the finishing process, the specimens' diameters were constantly verified with an electronic caliper (Starret, Microtec Instrumentos de Precisão M. E., Sao Paulo, Brazil), assuring accuracy of within 0.01 mm [4].

Radiographies of the joints were taken with radiographic film (Ektaspeed Plus, Eastman Kodak, Rochester, NY) to verify internal defects. The radiographic exam consisted of the exposure of the specimens to radiation (90 KV, 15 mA, 0.6 seconds and 10 to 13 mm of distance), using a periapical film [20]. The radiographies were visually analyzed for the presence of porosity in the joints.

Before the fatigue test, 3 extra randomly specimens at the same diameter were submitted to tensile tests to establish the mean yield strength at 0.2% permanent strain. The stress established for the fatigue test (262 MPa) was calculated as 30% of the mean yield strength. The loading frequency in the fatigue test was 15 Hz, and the loadings calculated were 463 N, 822 N and 2520 N, to 1.5, 2.0 and 3.5 mm diameters, respectively. The specimens were then submitted to fatigue strength tests using a testing machine (Test Star II, Material Testing System, MTS Systems Corp, Minneapolis, Minn) and the number of cycles required to cause the fatigue fracture were registered. The specimens were tested submerged in synthetic saliva (1.5 mM Ca, 3.0 mM P, 20.0 mM $NaHCO_3$, pH 7.0) [20] at room temperature to 100 000 cycles.

Fatigue fracture surfaces of representative specimens were examined using a scanning electron microscope (Electron Probe Microanalyser, Jeol model JXA 840 A, Jeol Ltd, Tokyo, Japan). The number of cycles obtained were analyzed by Kruskal-Wallis and

Dunn test (5%), and the data from the radiographic analyzes were correlated with the number of cycles by Spearman correlation coefficient (5%), to each diameter/distance, and to all grouped data.

## Results

Table I shows the median values of the number of cycles until fracture in the experimental groups. The number of cycles required until fracture was seen to be lower for all the diameters with 0.6 mm joint openings. The same was observed for the 3.5 mm diameter specimens when the joint opening was 0.0 mm.  All the specimens included in the control groups achieved over 100 000 cycles. The 1.5- and 2.0-mm diameter specimens that were tested with 0.0 mm joint openings behaved similarly to the control group specimens, without statistical differences.

The Spearman correlation coefficient (Table II) suggested that there was a negative correlation between the number of cycles and presence of porosity, except when the 1.5 mm groups were correlated. In these cases, when the number of cycles increased, the presence of porosity in the radiography decreased. Figures 1, 2 and 3 show SEM photomicrography of the fractured surfaces of the 1.5, 2.0 and 3.5 mm specimens, respectively. Figures 1A, 2A and 3A show the surface of 0.0 mm-joint opening. Figures 1B, 2B and 3B show the 0.6 mm-joint opening. The presence of internal porosity (arrow) was higher when the joint opening was 0.6 mm for the 1.5 mm- and 2.0 mm-diameter specimens. However, the internal porosity was smaller in these joint openings surfaces for the 3.5 mm specimens, when compared with 0.0 mm joint opening surface.

## Discussion

For successful treatment when employing implant-supported prostheses, a number of precautions are required during clinical and laboratorial procedures. The framework used must be strong and simultaneously passively fit the abutments surface [8]; slight mistakes during molding procedures, for example, can produce framework distortion [6]. Thus, to achieve passive fit, it is often necessary to cut the framework and repair it later with a welding procedure [17].

Despite the fact that the laser-welding technique has been reported to demonstrate lower HAZ and higher accuracy [3,5,8,11], problems such as increasing hardness and argon arrest are associated with this process, [16,17]. In this study, the HAZ hardness was not measured, however SEM photomicrographs (Figs. 1, 2 and 3) of fractured surfaces were taken. These photomicrographs show large pores inside the laser-welded zone, suggesting argon arrestment as a consequence of continuous argon spraying throughout the procedure and/or inadequate beam penetration [17,22]. In the 1.5 and 2.0 mm specimens with 0.6 mm joint openings, the presence of pores was higher than in the 0.0 mm openings, probably due to the increase in gas seizure in the 0.6 mm joints. The 0.6 mm-joint openings were slowly filled with a higher quantity of metal filler, proving a greater possibility of arresting argon gas. For the 3.5 mm-diameter specimens, the larger pores appeared in the 0.0 mm joint openings, suggesting inadequate beam penetration [17,22]. According to some authors, the laser beam penetrates a limited depth of 1.5 mm [9,16,23,24]. Thus, it is probable that the laser beam does not reach the center of the 3.5 mm specimens, as can be seen in Figure 3A.

The power of laser welding may be controlled and determined by two parameters: voltage and pulse duration [5]. Voltage controls the welding energy and an increase in voltage leads to a greater welding depth. Pulse duration determines the diameter of the welding spot. As such, the diameter of the welding spot will be larger if a longer pulse duration is used [5,24]. When the power of the laser welding is exceeded and the laser energy supply is prolonged, the temperature of the molten metal exceeds the boiling point and causes the molten metal to evaporate [24]. The increases in the volume of evaporated metal, compared with that of molten metal causes high pressure. The pressure of the evaporated metal creates turbulence in the molten metal and forms a cavity called keyhole [24,25]. It should be noted that despite the existence of numerous studies regarding laser welding in the literature, there is no established welding protocol. In this study, we used a higher power than that considered sufficient by Chai & Chou in 1998 [5]; this power, however, was not in excess, as shown by the fact that the 1.5 mm-diameter specimens with 0.0 mm-joint openings survived as much as the control groups. However, this power was not enough to permit the penetration depth of the laser beam in the 3.5 mm specimens. This study employed standardized welding parameters in relation to the specimens' diameters, and all the parameters were determined by an experienced professional.

Full contact of base metals is also associated with successful laser joints [9], which are difficult to attain. In this study, both joint openings were less resistant than the intact group to 3.5 mm specimens (Table I), suggesting that the "I" design of joints used in this study is not the best one for large diameters. Possibly another design, such as the "X" design [26] may permit better laser-welded joints. In this design, the center is maintained juxtaposed to the sections with thin diameters, permitting deep laser beam penetration.

Furthermore, the periphery is welded starting from the center until the surface of the specimen [26].

Implant-supported frameworks undergo repeated loading and fatigue fracture because of the cyclic mechanism of the masticatory system [4]. Fatigue strength is the stress at which a material fails under repeated loading after a certain number of cycles [3,13,17,27]. This fluctuating stress could range from values below the structural yield strength to those above it that are described respectively as high-cycle (low-stress) and low-cycle (high-stress) tests [3,4,17,19,27]. In this study, the established stress level was 30% of the mean yield strength calculated at 0.2% permanent strain. Thus, the stress selected for the fatigue test was a low stress for the control specimens that resisted over 100 000 cycles (high-cycles). This was established to permit the laser welding comparison between the groups. In a pilot study that employed a stress of 70% of the mean yield strength, as used by other studies [4,13,17], all the welded specimens fractured with a reduced number of cycles that will not permit the comparison between the experimental groups. The parameters utilized allowed the comparison of the fatigue strength in both factors studied (joint opening and diameter), demonstrating that for both narrow diameters (1.5 and 2.0 mm) and the juxtaposition of parts, the specimens survived a higher number of cycles, as observed for the intact groups.

With the intention of isolating the variables internal porosity and external irregularities inherent to the casting process and to the manual finishing process [3,4,13,27], machined specimens were used. Specimens were machined from pre-fabricated bars of Ti-6Al-4V grade V, the same that are used in prosthetic component. This variables act like stress raisers that influence fatigue test [19]. As such, it was possible to compare the laser-welding opening joints in different diameters, in an isolate way. A proof of this isolation was that all the broken specimens were fractured in the joint or near it (HAZ); and all the control specimens resisted 100 000 cycles.

With regard to the radiographic analyses of the joints, in contrast to a report by with Zavanelli *et al.*, in 2004 [17], it was possible visualize internal porosity inside the joints with these analyses, because the lower density of titanium alloys permitted the penetration of radiation into the structures analyzed, thus allowing the observation of porosity [4,13,20]. Interestingly, these analyses demonstrated a negative correlation, revealed by Spearman correlation coefficient (-0.5982), when all the groups were correlated. It was observed that as the number of cycles increased, the presence of porosity in the radiography decreased. This correlation indicates that internal porosity really acts as an stress raiser [19,27,28], decreasing the fatigue life of the prostheses. These imperfections lead to the development of microcracks, which coalesce and ultimately result in a microscopic crack and failure [13,17,27].

With regard to the results of this study, it may be concluded that radiographic examinations of the joint should be carried out before prosthesis installation to avoid the installation of fragile frameworks that are less resistant to bite cycles. However, it should be pointed out that this study did not aim to quantify laser-welded framework survival, since bite load and the number of masticatory cycles are extremely variable and depend on several factors [29]. As such, no conclusions may be made with regard to the number of years that welded frameworks will survive if the joint is made under the same conditions used in this study. The aim of this study was to compare the joint openings to affirm the best for use in prosthesis frameworks (diameter).

## Conclusions

This study allows us to draw the following conclusions:

1. Laser-welding of Ti-6Al-4V structures with a thin diameter provides the best conditions for the juxtaposition of parts.
2. For large diameters, both joint openings reduced fatigue life.
3. For titanium joints, radiographic examination allows the detection of internal voids, which can reduce fatigue life.

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**Table I.** Media number of cycles resisted in the experimental groups.

| Diameter | Distance | | |
|---|---|---|---|
| | Control | 0.0 mm | 0.6mm |
| 1.5 mm | 100000 Aa | 64304.5 Aa | 416 Ab |
| 2.0 mm | 100000 Aa | 65273 Aa | 3448 Ab |
| 3.5 mm | 100000 Aa | 116 Bb | 12260 Ab |

Median values followed by the same letter are not significantly different (Kruskal-Wallis / Dunn, alfa=5%). Capital letters compare diameters inside the level of the factor distance and small letters compare distances inside the level of diameter factor.

**Table II.** Association of number of cycles survived and absence of internal voids in radiography exam.

| | | Spearman Coefficient | (p)= |
|---|---|---|---|
| 1.5 mm Diameter | Distance 0.0 mm | * | * |
| | Distance 0.6 mm | -0.4264 | 0.2191 |
| 2.0 mm Diameter | Distance 0.0 mm | -0.9285 | 0.0001 |
| | Distance 0.6 mm | -0.8528 | 0.0017 |
| 3.5 mm Diameter | Distance 0.0 mm | -0.7218 | 0.0184 |
| | Distance 0.6 mm | -0.8704 | 0.001 |
| All distances / All diameters | | -0.5982 | < 0.0001 |

* All specimens were intact, thus correlation was impossible.

Spearman Coefficient (-1 a 1).

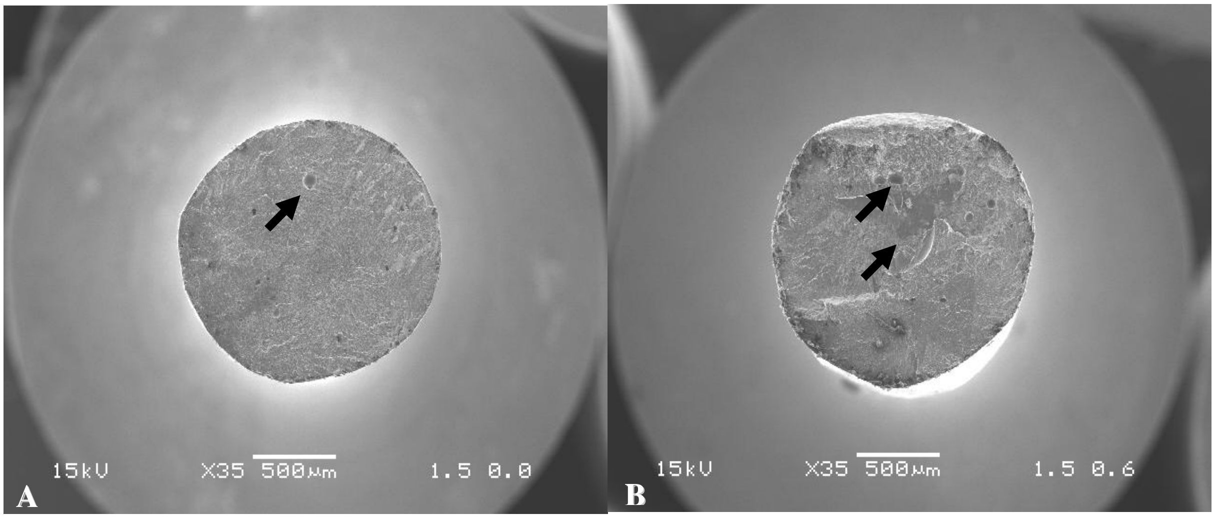


**Fig. 1:** SEM photomicrograph of fracture surface in 1.5 mm-diameter specimens: **A.** 0.0 mm joint opening / **B:** 0.6 mm joint opening.

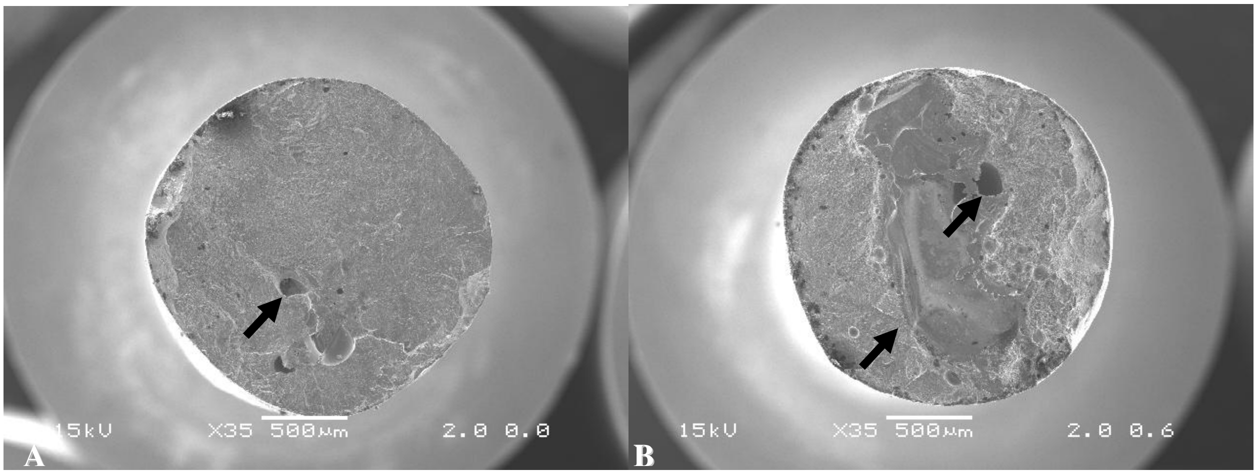


**Fig. 2:** SEM photomicrograph of fracture surface in 2.0 mm-diameter specimens: **A.** 0.0 mm joint opening / **B:** 0.6 mm joint opening.

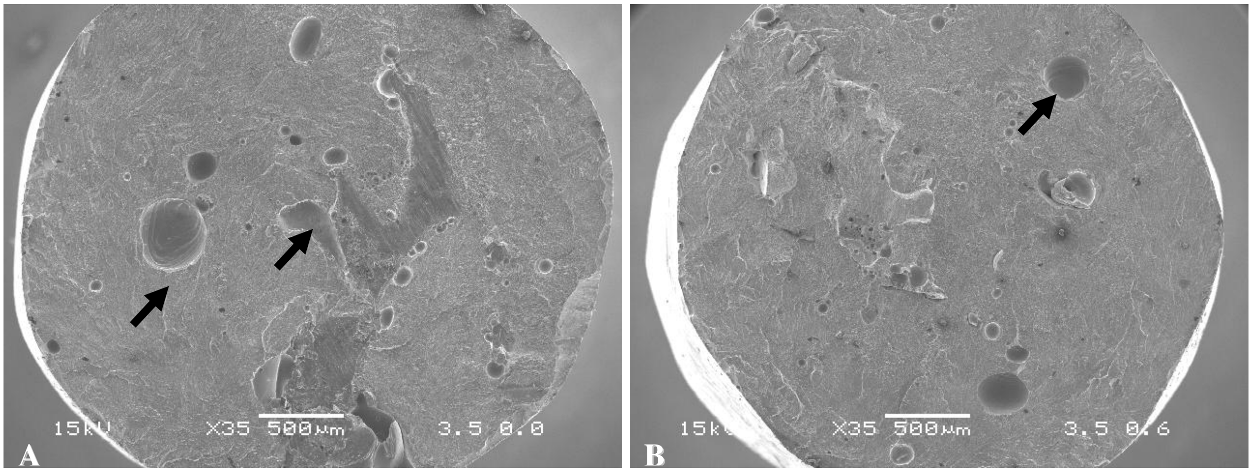


**Fig. 3:** SEM photomicrograph of fracture surface in 3.5 mm-diameter specimens: **A.** 0.0 mm joint opening / **B:** 0.6 mm joint opening.

# CAPÍTULO 5

## Fatigue performance of joints executed in pure titanium structures with several diameters


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# Fatigue performance of joints executed in pure titanium structures with several diameters


## Abstract

This study evaluated fatigue strength of pure titanium laser-welded joints. Ninety dumbbell rods with central diameters of 1.5, 2.0 and 3.5 mm were casted in pure titanium. Sixty specimens were sectioned in two halves and then welded using two joint openings (0.0 and 0.6 mm). The combination among variables created six groups, which associated with intact groups add up nine groups (n=10). Laser welding was executed as follows: 360V/8ms (1.5 and 2.0 mm) and 380V/9ms (3.5 mm) with focus and frequency regulated to zero. Joints were finished, polished and submitted to radiographic examination to visually analyze internal porosity presence. Specimens were then submitted to mechanical cyclic test, and the number of cycles until failure was recorded. Fractured surfaces were examined with scanning electron microscope (SEM). The numbers of cycles required for fracture was lower for all the diameters with 0.6 mm joint openings, and for 3.5 mm diameter with 0.0 mm joint openings. There was negative correlation between number of cycles and porosity presence. Than for Ti cp frameworks with thin diameters, laser welding is better when structures are juxtaposed, and that specimens with radiographic internal voids in the joints are more susceptible to fail.



**Key words:** Titanium; Casting; Laser; Fatigue.


## Introduction

Since the introduction of titanium in the early 1950s, this material has, in a relative short time, become backbone materials for the aerospace, energy and chemical industries [1-3]. The combination of high fatigue strength and high corrosion resistance makes titanium the best material choice for many critical applications [1-3]. In the last decades (1970s), titanium's use has expanded to include applications in medical prostheses due to the excellent biocompatibility [2]. In dentistry this was not different; titanium was initially used in implants manufacture, and the prostheses supported by this implants were made in precious metals. But due to the high cost of these metals, they were replaced by semi-precious metals [3]. However, they present some disadvantages like low corrosion resistance, insufficient cervical fit and possible allergic reactions to some elements such as nickel and beryllium [3, 4]. In front of these problems, studies about titanium's use to prostheses frameworks making had begun [3, 5 - 8].

Titanium and its alloys possess some characteristics that are equal or better than types III and IV gold dental alloys and presents cheap cost [2, 3, 9]. It presents excellent biocompatibility, high corrosion resistance, desirable physical properties, low cost, low density and low thermal conductibility [3, 5, 7, 8]. The low density associated with the low atomic number confers to titanium low radiopacity grade that permits radiographic analyses to visualize internal voids in titanium casted frameworks [10, 11].

Many types of titanium alloys are available but the Ti-6Al-4V alloy is the most commonly used, since its physical and mechanical properties are superior to those of commercially pure titanium [3], and similar to those of Ni-Cr and Co-Cr. However, commercially pure titanium presents good weldability, and Ti-6Al-4V, fair weldability [12].

Implant prostheses require more accurate fit than natural teeth prostheses because of the lack of periodontal tissues that compensate for minor relationship errors [8]. There are unavoidable errors in impression procedures [13, 14] and/or cast distortion for frameworks that can cause misfit of the frameworks. To avoid misfit, in some cases it is necessary to section the framework and joint it later on [2, 15]. The titanium welding procedure must be achieved with "laser" or electric arc welding [16, 17], due to these procedures employ argon shielding in the welding chambers that maintain an argon inert atmosphere to prevent the metal contamination [15, 18, 19]. This metal needs this protector atmosphere because it reacts to air gases when heated above 600°C temperatures [5, 20].

Welding process has greatest potential for affecting materials properties; usually increasing hardness, decreasing tensile strength and ductility [1, 15, 21]. Several reports on laser welding of titanium have shown raise hardness in the welded zone and presence of large pores in the laser-repaired joints [9, 18]. However, this technique has demonstrated a smaller heat-affect zone (HAZ), reduced joining distortions, lower damage to veneering coverage and close yield strength to the base metal under static conditions [8, 15, 22].

Fatigue, which is the process of progressive localized permanent structural change occurring in a material subjected to cyclic loading, is responsible for 90% of all service failures due to mechanical causes [23]. This process is usually initiated by stress raisers such as voids, inclusions, notches, surface roughness modifiers and metallurgical variables. During chew, dental restorations are continuously subjected to courses of alternation stress due to sideways movements of the mandible during comminution of foodstuffs [17].

Despite a better fit, the laser-welded frameworks must not present the same fatigue strength as compared to intact structures. So, this study was carried out to evaluate the fatigue strength of pure titanium laser-welded joints with several diameters and joint openings and to correlate the results with the presence of internal voids observed in the radiographic analyses.

## Material and Methods

Dumbbell shaped rods were made in acrylic resin Duralay II (DuraLay, Reliance Dental Mfg Co, Chicago, USA) on a metal matrix, with diameters of 1.5, 2.0 and 3.5 mm in the central segment. The dumbbell rods dimensions were based on norm ASTM E8M-04 [24]. These acrylic specimens were visually observed to evaluate any flaw in the structures and casted in a vacuum injection titanium casting machine (Rematitan System, Dentaurum, Pforzheim, Germany) with commercially pure titanium (CP Ti). To accomplish this, acrylic resin patterns of each specimen were invested (Rematitan Plus, Dentaurum, Germany) using a 250g powder and 40 mL liquid ratio that were mixed under vacuum, according to the manufacturer's instructions. Invested specimens were heated using a slow heat cycle [23] for wax removal, after setting. The specimens were casted using 36g CP Ti ingots following identical manufacturing procedures. Molds were immediately immersed in cold running water after casting.

Specimens were divested with the help of a pneumatic hammer (M320, Flli Manfredi, Sofia, Italy) and airborne particles abraded at a pressure of 80 $lbf/in^2$ with 100 μm aluminum oxide particles. The specimens were finished and polished using special titanium drills (Rematitan, Dentaurum, Pforzhein, Alemanha), rubbers nº 5001 polisher (Dedeco Dental, New York, USA) and titanium polishing paste (Tiger Brilliant Polier Paste, Dentaurum, Pforzheim, Alemanha). Specimens' diameters were constantly verified with an electronic caliper (Starret, Microtec Instrumentos de Precisão M. E., Sao Paulo, Brazil) during finishing process, assuring accuracy within 0.01 mm [23].

Radiographies of the specimens were then taken with radiographic film (Ektaspeed Plus, Eastman Kodak, Rochester, USA) to verify internal defects. The radiographic exam consisted of the exposure of the specimens to radiation (90 KV, 15 mA, 0.6 second and 10 to 13 mm of distance), using a periapical film [11]. The specimens that presented voids in dumbbell rods central diameter were excluded.

Sixty specimens, twenty in each diameter, were sectioned in half, perpendicularly to the long axis. The jointed portions were lined up in a metal matrix in order to maintain distances of 0.0 and 0.6 mm between them. The aligned specimens were fixed with acrylic resin Duralay II (DuraLay, Reliance Dental Mfg Co, Chicago, USA), respecting the welded distances (0.0 and 0.6 mm). The specimens were then invested in type IV gypsum and after the gypsum crystallization the resin was removed with a wire cutter. The metal adjacent to the gap was airborne particles abraded at a pressure of 80 lbf/in$^2$ with 100 $\mu$m aluminum oxide particles and the joints were welded on opposite sides of the specimen to stabilize them. The gypsum was then removed and welding was carried out using energy of 360V/8ms (1.5 and 2.0 mm specimens) and 380V/9ms (3.5 mm specimens), with the focus and frequency calibrated at zero using a Desktop –F (Dentaurum, Pforzhein, Germany) laser machine. The welding process was performed by a trained and competent professional.

Three diameters and two joint distances were used to simulate the following situations: 1.) 1.5 mm of central diameter, three elements fixed prosthesis frameworks; 2.) 2.0 mm of central diameter, overdenture bars; 3.) 3.5 mm of central diameter, ten element fixed prosthesis frameworks; 4.) 0.0 mm joint opening, precast cut; 5.) 0.6 mm joint opening, cut with a thin disc. The combination between the variables created six groups (n=10), which together with the controls groups (intact) made a total of 9 groups.

After the welding process, the joints were finished and polished as like was done after casting process, and radiographies of the joints were taken the same way, either. Theses radiographies were visually analyzed for the presence of internal voids in the joint.

Three randomly extra intact specimens at the same diameter were submitted to tensile tests, before fatigue test, to establish the mean yield strength at 0.2% permanent strain. The stress established for the fatigue test (189 MPa) was calculated as 30% of the mean yield strength. The loading frequency in the test was 15 Hz, and the loadings calculated were 334 N, 593 N and 1818 N, to 1.5, 2.0 and 3.5 mm diameters, respectively. The specimens were then submitted to fatigue strength tests using a testing machine (Test Star II, Material Testing System, MTS Systems Corp, Minneapolis, Minn) and the number of cycles required to cause the fatigue fracture were registered. The specimens were tested submerged in synthetic saliva (1.5 mM Ca, 3.0 mM P, 20.0 mM $NaHCO_3$, pH 7.0) [24] at room temperature to 100 000 cycles.

Fatigue fracture surfaces of representative specimens were examined using a scanning electron microscope (Electron Probe Microanalyser, Jeol model JXA 840 A, Jeol Ltd, Tokyo, Japan). The number of cycles obtained were analyzed by Kruskal-Wallis and Dunn test (5%), and the data from the joint radiographic analyzes were correlated with the number of cycles by Spearman correlation coefficient (5%), to each diameter/distance, and to all grouped data.

## Results

Table I shows the median values of the number of cycles until fracture in the experimental groups. The number of cycles required until specimens fracture was seen to be lower for all the diameters with 0.6 mm joint openings. The same was observed for the 3.5 mm diameter specimens when the joint opening was 0.0 mm. The 1.5- and 2.0-mm diameter specimens that were tested with 0.0 mm joint openings behaved similarly to the control group specimens, without statistical differences. Some of them achieved over 100.000 cycles, and a good deal of the others fractured distant the joints.

The Spearman correlation coefficient (Table II) suggested that there was a negative correlation between the number of cycles and presence of porosity in radiography. In these cases, when the number of cycles increased, the porosity presence decreased.

Figures 1, 2 and 3 show SEM photomicrography of the fractured surfaces of 1.5, 2.0 and 3.5 mm specimens, respectively. Figures 1A, 2A and 3A show the surface of 0.0 mm-joint opening. Figures 1B, 2B and 3B show the 0.6 mm-joint opening. The presence of internal porosity (arrows) was high when the joint opening was 0.6 mm for all diameters. However, internal porosity was also high in the 0.0 mm joint openings surfaces for the 3.5 mm specimens (Fig. 3A)

## Discussion

Titanium implant-supported frameworks must be strong and simultaneously passively fit the abutments surface when the successful treatment is desired [15]. Slight distortions occurred by molding and casting technique inherent of these processes, for instance, can carry to ill success [13, 14]. Thus, to achieve passive fit, it is often necessary to cut the framework and repair it later with a welding procedure [9]. However, when the framework has to be welded its fatigue strength must decreases.

Despite the fact that the laser-welding technique has been reported to demonstrate lower HAZ and higher accuracy [8, 15, 17, 26], problems such as increasing hardness and argon arrest are associated with this process [9, 18]. However, it is important to remember that commercially pure titanium's weldability is considered good [12], due to this metal at room temperature has an alpha (hexagonal close-packed) crystal, and titanium's weldability decreases with increases levels of $\beta$-stabilizers [17].

In this study SEM photomicrographs (Figs. 1, 2 and 3) of fractures surface show large pores inside the laser-welded zone, suggesting argon arrestment as a consequence of continuous argon spraying throughout the procedure and/or inadequate beam penetration [9, 16]. For all specimens with 0.6 mm joint openings, the incidence of pores was high (Fig. 1B, 2B and 3B). Probably due to in these joint openings the possibility of arresting argon gas is higher. These larger joint openings are slowly filled with a higher quantity of metal filler. And the specimens that represented the groups of 0.6 mm joint openings resisted less to fatigue test (Table I) than the control groups. Hence, these results associated with the Spearman Coefficients for these groups' permits the affirmation that the 0.6 mm distance motive argon arrestment and consequentially porous establishment that decrease the fatigue strength.

However for 3.5 mm-diameter specimens, larger pores appeared in 0.0 mm joint openings either. This appearance suggests inadequate beam penetration [9, 16]. According some authors, the laser beam penetrates a limited depth of 1.5 mm [18, 22, 27, 28]. Thus, it is probable that the laser beam does not reach the center of the 3.5 mm specimens, as can be seen in Figure 3A. However, Wiskott *et al.*, in 2001 [17] contradicting Wang & Welsh, in 1995 [26], affirmed that their welding parameters (280 V/ 0.6ms) achieved full depth of 3.4 mm central bars joints executed in CP Ti. This was contradicted in this study. Their welding parameters were less powerful than ones employed in this study, but they did not utilize the same as cast CP Ti. They annealed the specimens homogenizing the grain structure and relieving internal stress. Some authors have reported that residual internal stress may be associated with the occurrence of internal flows in welded titanium [29]. So the residual internal relief could have modified the weldability of CP Ti.

The power of laser welding may be controlled and determined by two parameters: voltage and pulse duration [8]. Voltage controls the welding energy and an increase in voltage leads to a greater welding depth. Pulse duration determines the diameter of the welding spot. As such, the diameter of the welding spot will be larger if longer pulse duration is used [8, 28]. When the power of the laser welding is exceeded and the laser energy supply is prolonged, the temperature of the molten metal exceeds the boiling point and causes the molten metal to evaporate [28]. The increases in the volume of evaporated metal compared with that of molten metal causes high pressure. The pressure of the evaporated metal creates turbulence in the molten metal and forms a cavity called a keyhole [28, 30]. It should be noted that despite the existence of numerous studies regarding laser welding in the literature, there is no established welding protocol. In this study, it was used higher power than that considered sufficient by Chai & Chou in 1998 [8]; this power, however, was not in excess, as shown by the fact that the 1.5 mm-diameter specimens with 0.0 mm-joint openings survived as much as the control groups and the SEM photomicrography of these specimens (Fig. 1A) did not shows these keyhole cavities. However, this power was not enough to permit the penetration depth of the laser beam in the 3.5 mm specimens. This study employed standardized welding parameters in relation to the specimens' diameters, and all the parameters were determined by an experienced professional.

The success of laser joints is associated with full contact of base metals parts [22], which are difficult to attain clinically. In this study, this was real for 1.5 and 2.0 mm specimens. However, for 3.5 mm specimens it was not; both joint openings were less resistant than the intact group for this diameter (Table I), suggesting that the "I" design of joints used in this study is not the best one for large diameters. Possibly another design, such as the “X” design [31] may permit better laser-welded joints. In this design, the center is maintained juxtaposed to the sections with thin diameters, permitting deep laser beam penetration. Furthermore, the periphery is welded starting from the center until the surface of the specimen [31].

The established stress to this study differ the stress used by other similar studies [9, 20, 23]. In a pilot study that employed a stress of 70% of the mean yield strength, as used by these studies, all the welded specimens fractured with a reduced number of cycles that will not permit the comparison between the experimental groups. Reducing the stress (30% of the mean yield strength) the comparison of the fatigue strength in both factors studied (joint opening and diameter) was possible.

With regard to the radiographic analyses of the joints, in contrast to Zavanelli *et al.*, in 2004 [9], it was possible visualize internal porosity inside the joints with these analyses, because the lower density of titanium alloys permitted the penetration of radiation into the structures analyzed, thus allowing the observation of porosity [11, 10, 20]. Interestingly, these analyses demonstrated a negative correlation, revealed by Spearman correlation coefficient (-0.7604), when all the groups were correlated. It was observed that as the number of cycles increased, the presence of porosity in the radiography decreased. This correlation indicates that internal porosity acts as stress raiser [32, 33], decreasing the fatigue life of the prostheses. These imperfections lead to the development of microcracks, which coalesce and ultimately result in a microscopic crack and failure [9, 20].

With the intention of to simulate clinical situation, the specimens were casted in this study. And to isolating the variables internal porosity inherent to the casting process [20, 23], radiographies of the specimens were taken to exclude faulty casted specimens. However, some specimens of control groups fractured, and some of the others did not fracture in the joint or near it (HAZ). Perhaps some irregularity like inclusions cannot be seen in the radiographic exam; or the manual finishing and polishing after casting process, even standardized influenced the crack initiation and propagation [20].

## Conclusions

Within the limitation of this study, the following conclusion can be drawn:

1. Radiographic examinations of the joint should be carried out before approval frameworks to avoid the installation of fragile prostheses.
2. To solder CP Ti with thin diameter the best condition is the juxtaposition of parts.
3. For large diameters both joint openings reduced fatigue life.

## Acknowledgements

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# Appendix

**Table I.** Media number of cycles resisted in the experimental groups.

| Diameter | Distance | | |
|---|---|---|---|
| | Control | 0.0 mm | 0.6mm |
| 1.5 mm | 87720 Aa | 100000 Aa | 39829.5 Ab |
| 2.0 mm | 98153.5 Aa | 95421.5 Aa | 16502.5 Ab |
| 3.5 mm | 100000 Aa | 1257.5 Bb | 14325.5 Ab |

Median values followed by the same letter are not significantly different (Kruskal-Wallis / Dunn, alfa=5%). Capital letters compare diameters inside the level of the factor distance and small letters compare distances inside the level of diameter factor.

**Table II.** Association of number of cycles survived and absence of internal voids in radiography exam.

| | | Spearman Coefficient | (p)= |
|---|---|---|---|
| 1.5 mm Diameter | Distance 0.0 mm | * | * |
| | Distance 0.6 mm | -0.7977 | 0.0057 |
| 2.0 mm Diameter | Distance 0.0 mm | -0.9097 | 0.0003 |
| | Distance 0.6 mm | -0.8528 | 0.0017 |
| 3.5 mm Diameter | Distance 0.0 mm | -0.7977 | 0.0057 |
| | Distance 0.6 mm | -0.8528 | 0.0017 |
| All distances / All diameters | | -0.7604 | < 0.0001 |

* None radiography presented voids, thus correlation was impossible.

Spearman Coefficient (-1 a 1).

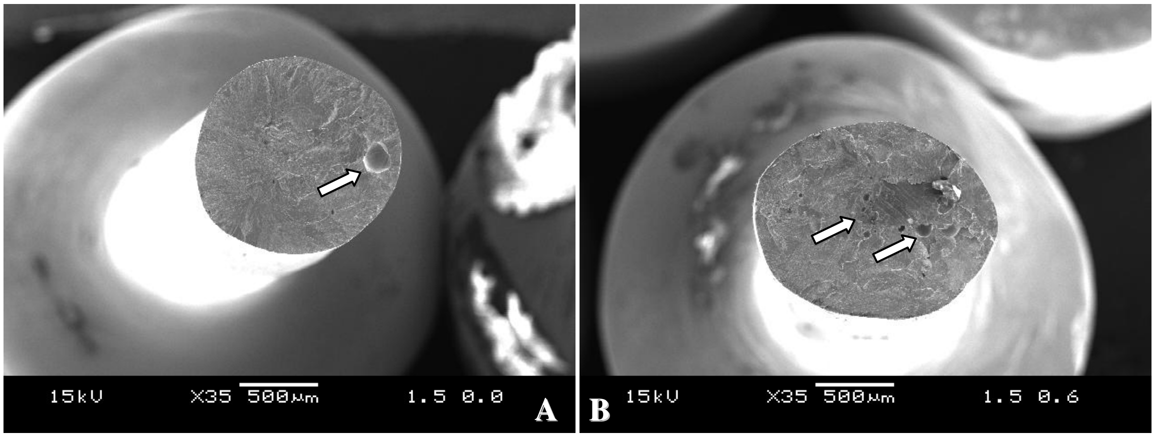


**Fig. 1:** SEM photomicrograph of fracture surface in 1.5 mm-diameter specimens: **A.** 0.0 mm joint opening / **B:** 0.6 mm joint opening.

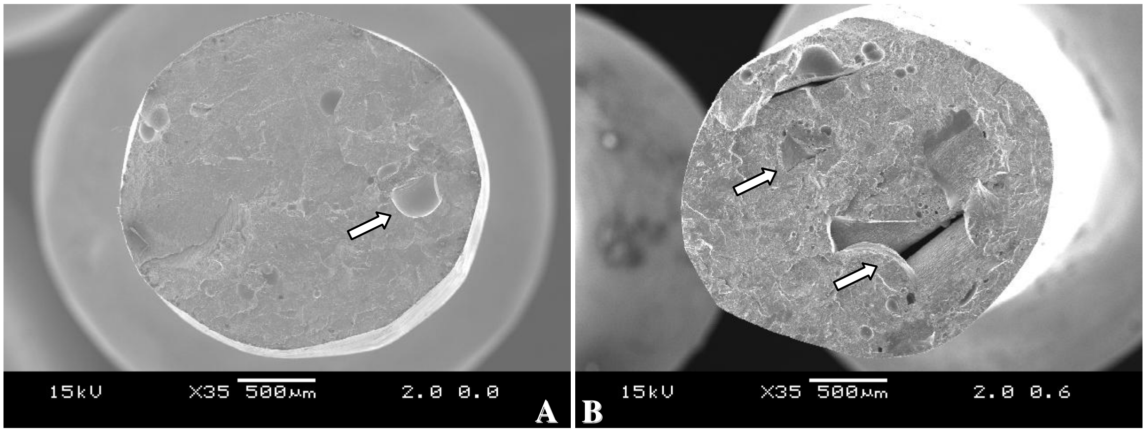


**Fig. 2:** SEM photomicrograph of fracture surface in 2.0 mm-diameter specimens: **A.** 0.0 mm joint opening / **B:** 0.6 mm joint opening.

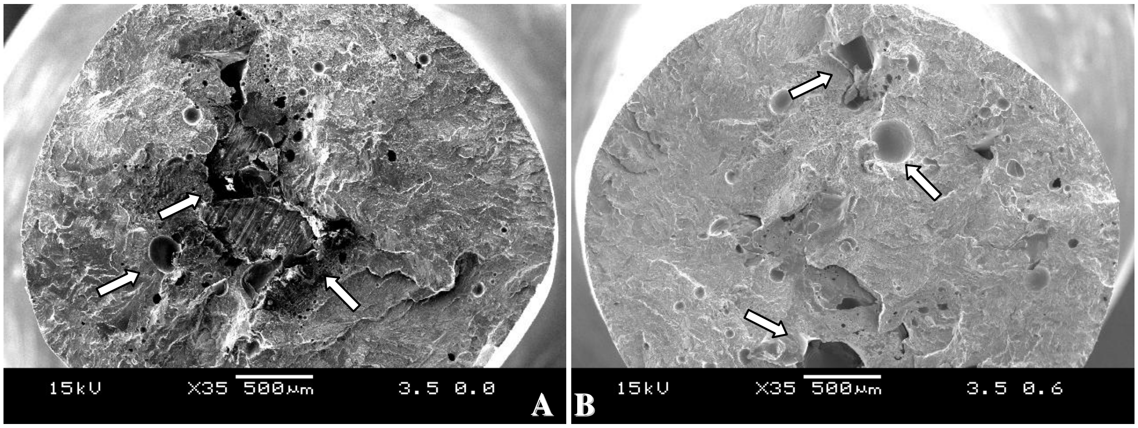


**Fig. 3:** SEM photomicrograph of fracture surface in 3.5 mm-diameter specimens: **A.** 0.0 mm joint opening / **B:** 0.6 mm joint opening.

# 3. CONSIDERAÇÕES GERAIS

De modo geral, pode-se observar diante dos resultados desses estudos, que o exame radiográfico proposto por Zavanelli & Henriques em 2001 permite a visualização de porosidades tanto em estruturas fundidas em titânio comercialmente puro, quanto em uniões soldadas a laser em Ti cp e em ligas de Ti-6Al-4V, o que contradiz os relatos de Botega (2005) que afirmou não ser possível verificar a presença de porosidades internas em espécimes fundidos em Ti cp, através da análise radiográfica. Além de contradizer os relatos de Zavanelli *et al.* em 2004, que afirmaram não ser possível realizar essa análise em uniões soldadas a laser em liga de Ti-6Al-4V e em Ti cp, sem tecer considerações a cerca dos motivos, sendo possível entretanto, visualizá-las em radiografias de estruturas fundidas.

A baixa densidade do titânio permite a penetração de radiação nas estruturas confeccionadas nesse material (Wang & Boyle, 1993; Zavanelli & Henriques, 2001). Além disso, seu baixo número atômico lhe confere baixa radiopacidade (Zavanelli & Henriques, 2001). Assim, há possibilidade de visualização de defeitos internos nas estruturas fundidas (Wang & Boyle, 1993; Zavanelli & Henriques, 2001; Zavanelli *et al*., 2004; Guilherme *et al*., 2005) e soldadas em titânio e suas ligas.

Pode-se observar também, que a soldagem a laser de espécimes delgados (1,5 e 2,0 mm) com espaçamento entre as partes a serem soldadas, gera uniões de qualidade inferior quando comparadas às uniões com justaposição das partes, para ambos os materiais estudados. Essa situação foi resultado da maior facilidade de aprisionamento de gás argônio nas uniões com maiores aberturas das juntas. Quando a fenda gerada é maior, utiliza-se maior quantidade de metal de adição para preenchê-la, aumentando a possibilidade de aprisionamento de gás.

Para os espécimes de 3,5 mm, pode-se observar que a qualidade da união gerada para ambos os materiais é ruim, independentemente da distância de soldagem. Isso ocorreu devido à insuficiente penetração do feixe de laser nas uniões com justaposição das partes (Sjögren *et al.*, 1988; Wang & Fenton, 1996), e ao aprisionamento de gás nas uniões com espaço entre as partes (0,6 mm). Quanto menor a profundidade alcançada pelo feixe de laser, maior a quantidade de vazios internos (Baba & Watanabe, 2005). Segundo diversos autores, essa penetração é limitada a 1,5 mm de profundidade (Roggensach *et al.*, 1993; Neo *et al.*, 1996; Tambasco *et al.*, 1996; Baba & Watanabe, 2005).

Além disso, notou-se haver correlação negativa entre número de ciclos e presença de porosidades internas nas radiografias em uniões realizadas em ambos os materiais estudados. Quanto maior o número de ciclos, menor a incidência de porosidades nas radiografias analisadas. Com isso, depara-se com uma excelente maneira de realizar o controle de qualidade das uniões soldadas a laser, sendo muito importante a realização dessa análise por parte do cirurgião dentista, na sessão de aprovação da infra-estrutura soldada. Todavia, é muito importante ressaltar que nesse estudo, não foi avaliada a quantidade de porosidade, nem o tamanho das mesmas.

Quanto ao comportamento dos materiais, ao serem analisadas as tabelas dos valores originais (Apêndice), percebe-se que os valores médios resistidos pelos espécimes usinados em liga de Ti-6Al-4V foram numericamente inferiores aos valores resistidos pelos espécimes fundidos em Ti cp. Sabe-se que as propriedades mecânicas da liga de Ti-6Al-4V superam às do Ti cp (Lampman, 1990; Wang & Fenton, 1996; Guilherme *et al.*, 2005). Entretanto, sabe-se também, que o titânio cp apresenta melhor soldabilidade que essa liga (Lampman, 1990), e que a soldabilidade do mesmo decresce à medida que os níveis de estabilizadores β aumentam (Wiskott *et al.*, 2001), sendo o vanádio um exemplo de β-estabilizador (Lampman, 1990). Zavanelli *et al.* em 2004 analisaram a resistência à fadiga-corrosão de espécimes intactos confeccionados em liga de Ti-6Al-4V e em Ti cp, e após a fratura realizaram a união dos espécimes por meio de procedimento de soldagem a laser testando-os novamente, verificando não haver diferença estatística entre os materiais.

Alguns autores discorreram a respeito da presença de falhas internas ocasionadas por aumento da ductilidade do titânio ocasionadas por incompatibilidade dos cristais na estrutura cristalina α-β (Wiskott *et al.,* 2001), que gera tensões residuais internas. A estrutura cristalina do titânio pode ser α (hexagonal de corpo fechado) ou β (cúbica de corpo centrado) (Lampman, 1990). O Ti cp, em temperatura ambiente apresenta estrutura cristalina α, e a liga de Ti-6Al-4V, α-β (Lampman, 1990). Dessa maneira, uniões soldadas em ligas α-β têm maior probabilidade de apresentar falhas internas, e de fraturar com pouca deformação plástica. A ductilidade da região soldada nessas ligas, pode ser melhorada através do tratamento térmico pós-soldagem (Lampman, 1990; Wiskott *et al.*, 2001). Desse modo, estudos comparativos utilizando-se espécimes usinados em Ti cp e fundidos em liga de Ti-6Al-4V devem ser realizados utilizando-se os mesmos parâmetros que os utilizados nesse estudo, para que se possa comparar a soldabilidade desses materiais.

Percebe-se também, nesse estudo, que os corpos de prova fundidos em Ti cp falharam em regiões próximas a solda, ou distante dela; já para os espécimes usinados em liga de Ti-6Al-4V, essa falha ocorreu sempre próxima à solda. Provavelmente isso ocorreu devido ao fato de serem difíceis de isolar as variáveis externas inerentes ao processo de fundição, e ao processo de acabamento e polimento manual, as quais interferem diretamente na resistência à fadiga dos materiais. Com isso percebe-se que quando se pretende avaliar a qualidade da solda, o emprego de corpos de prova usinados é recomendado.

Existe ainda a necessidade de realização de novos estudos a cerca do design da união soldada em Ti cp e liga de Ti-6Al-4V, em corpos de prova de diâmetros maiores. Contudo, pode-se dizer que apesar das limitações desse estudo, puderam ser fornecidos dados importantes para o esclarecimento do comportamento da união soldada a laser em Ti cp e em liga de Ti-6Al-4V, nas condições estudadas.

# 4. CONCLUSÃO

Com base nos resultados obtidos e dentro das limitações dos presentes estudos, pode-se concluir que:

1. É possível visualizar radiograficamente porosidade interna em estruturas fundidas em Ti cp e em uniões soldadas a laser executadas em Ti cp e em liga de Ti-6Al-4V;

2. Para espécimes fundidos em Ti cp, a incidência de porosidade interna é maior em espécimes de diâmetros mais delgados (1,5 mm), principalmente quando a avaliação é feita em toda a extensão do espécime;

3. Em espécimes soldados de diâmetros delgados, para ambos os materiais, essa incidência é maior quando há espaçamento entre as partes;

4. Conforme aumenta a presença de porosidade interna verificada nas radiografias, diminui a resistência à fadiga dos espécimes para todas as situações, e em ambos os materiais;

5. Para soldar a laser estruturas de diâmetros delgados, confeccionadas em Ti cp ou em liga de Ti-6Al-4V, a melhor condição se dá com justaposição das partes;

6. Para espécimes de diâmetros maiores, ambas as situações estudadas apresentaram falhas, devendo-se estudar novos designs de união para aperfeiçoar essa união.

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* De acordo com a norma da UNICAMP/FOP, baseada na norma do International Committee of Medical Journal Editors – Grupo de Vancouver. Abreviatura dos periódicos em conformidade com Medline.

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# APÊNDICE

## VALORES ORIGINAIS

**Tabela 1.** Valores originais do número de ciclos até a fratura para os corpos de prova intactos usinados em liga de Ti-6Al-4V.

| Diâmetro / Corpo de prova | 1,5 mm | 2,0 mm | 3,5 mm |
|---|---|---|---|
| 1 | 100 000 | 100 000 | 100 000 |
| 2 | 100 000 | 100 000 | 100 000 |
| 3 | 100 000 | 100 000 | 100 000 |
| 4 | 100 000 | 100 000 | 100 000 |
| 5 | 100 000 | 100 000 | 100 000 |
| 6 | 100 000 | 100 000 | 100 000 |
| 7 | 100 000 | 100 000 | 100 000 |
| 8 | 100 000 | 100 000 | 100 000 |
| 9 | 100 000 | 100 000 | 100 000 |
| 10 | 100 000 | 100 000 | 100 000 |
| **Mediana** | 100 000 | 100 000 | 100 000 |
| **Média** | 100 000 | 100 000 | 100 000 |
| **Desv. Padrão** | 0 | 0 | 0 |

**Tabela 2.** Valores originais do número de ciclos até a fratura para os corpos de prova usinados em liga de Ti-6Al-4V, e soldados com distância 0,0 mm.

| **Diâmetro** / **Corpo de prova** | **1,5 mm** | **2,0 mm** | **3,5 mm** |
|---|---|---|---|
| 1 | 100000 | 12702 | 109 |
| 2 | 100000 | 100000 | 292 |
| 3 | 100000 | 15707 | 26 |
| 4 | 28609 | 18443 | 2406 |
| 5 | 15080 | 1154 | 58 |
| 6 | 100000 | 30546 | 855 |
| 7 | 1936 | 100000 | 25 |
| 8 | 100000 | 100000 | 123 |
| 9 | 12592 | 100000 | 5708 |
| 10 | 20778 | 100000 | 98 |
| **Mediana** | 64304,5 | 65273 | 116 |
| **Média** | 57899,5 | 57855,2 | 970 |
| **Desv. Padrão** | 44865,72 | 44981,9 | 1820,216 |

**Tabela 3.** Valores originais do número de ciclos até a fratura para os corpos de prova usinados em liga de Ti-6Al-4V, e soldados com distância 0,6 mm.

| **Diâmetro** / **Corpo de prova** | **1,5 mm** | **2,0 mm** | **3,5 mm** |
|---|---|---|---|
| 1 | 44 | 756 | 142 |
| 2 | 14436 | 775 | 1036 |
| 3 | 512 | 180 | 14562 |
| 4 | 189 | 9661 | 14172 |
| 5 | 320 | 294 | 22466 |
| 6 | 135 | 6121 | 13600 |
| 7 | 28 | 641 | 10920 |
| 8 | 60502 | 15116 | 227 |
| 9 | 4070 | 7841 | 16869 |
| 10 | 2380 | 15039 | 2954 |
| **Mediana** | 416 | 3448 | 12260 |
| **Média** | 8261,6 | 5642,4 | 9694,8 |
| **Desv. Padrão** | 18882,68 | 6057,896 | 8002,554 |

**Tabela 4.** Valores originais do número de ciclos até a fratura para os corpos de prova intactos fundidos em Ti cp.

| **Diâmetro** / **Corpo de prova** | **1,5 mm** | **2,0 mm** | **3,5 mm** |
|---|---|---|---|
| 1 | 72804 | 100000 | 71177 |
| 2 | 53617 | 76380 | 50105 |
| 3 | 70698 | 100000 | 61225 |
| 4 | 100000 | 96307 | 54206 |
| 5 | 65657 | 100000 | 100000 |
| 6 | 100000 | 75093 | 100000 |
| 7 | 100000 | 100000 | 100000 |
| 8 | 100000 | 100000 | 100000 |
| 9 | 90873 | 76542 | 100000 |
| 10 | 84567 | 52345 | 100000 |
| **Mediana** | 87720 | 98153,5 | 100000 |
| **Média** | 83821,6 | 87666,7 | 83671,3 |
| **Desv. Padrão** | 17104,67 | 16640,23 | 21742,44 |

**Tabela 5.** Valores originais do número de ciclos até a fratura para os corpos de prova fundidos em Ti cp, e soldados com distância 0,0 mm.

| **Diâmetro** / **Corpo de prova** | **1,5 mm** | **2,0 mm** | **3,5 mm** |
|---|---|---|---|
| 1 | 100000 | 12304 | 8688 |
| 2 | 100000 | 22502 | 930 |
| 3 | 100000 | 30562 | 8851 |
| 4 | 100000 | 100000 | 3089 |
| 5 | 100000 | 100000 | 1405 |
| 6 | 100000 | 100000 | 128 |
| 7 | 89342 | 100000 | 1110 |
| 8 | 49304 | 100000 | 177 |
| 9 | 38842 | 90843 | 1434 |
| 10 | 90723 | 50896 | 142 |
| **Mediana** | 100000 | 95421,5 | 1257,5 |
| **Média** | 86821,1 | 70710,7 | 2595,4 |
| **Desv. Padrão** | 23029,47 | 37170,16 | 3369,763 |

**Tabela 6.** Valores originais do número de ciclos até a fratura para os corpos de prova fundidos em Ti cp, e soldados com distância 0,6 mm.

| Diâmetro / Corpo de prova | 1,5 mm | 2,0 mm | 3,5 mm |
|---|---|---|---|
| 1 | 100000 | 18002 | 36667 |
| 2 | 4687 | 45987 | 32129 |
| 3 | 46183 | 31001 | 110 |
| 4 | 50762 | 26575 | 112 |
| 5 | 1070 | 15003 | 220 |
| 6 | 7608 | 456 | 21542 |
| 7 | 35980 | 50678 | 1429 |
| 8 | 43679 | 11036 | 14761 |
| 9 | 51561 | 1344 | 22282 |
| 10 | 35423 | 12209 | 13890 |
| **Mediana** | 39829,5 | 16502,5 | 14325,5 |
| **Média** | 37695,3 | 21229,1 | 14314,2 |
| **Desv. Padrão** | 29244,24 | 17209,94 | 13748,77 |

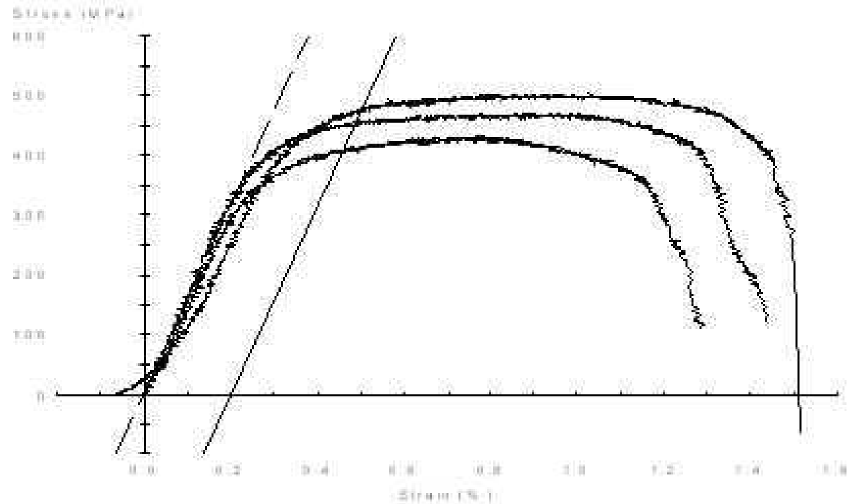


**Gráfico 1.** Curvas Tensão x Deformação para os 3 corpos de prova fundidos extras tracionados.

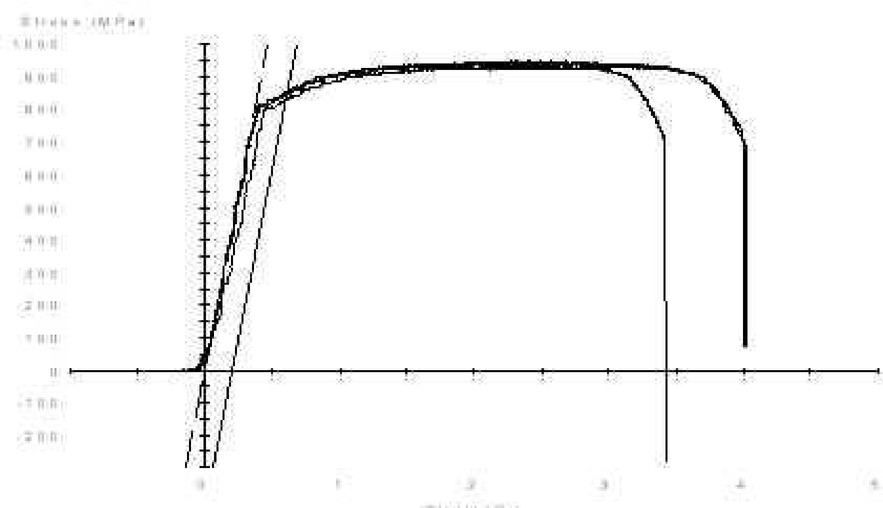


**Gráfico 2.** Curvas Tensão x Deformação para os 3 corpos de prova usinados extras tracionados.

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