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Comparative study on torsional strength, ductility and fracture characteristics of laser-welded $\alpha + \beta$ Ti–6Al–7Nb alloy, CP Titanium and Co–Cr alloy dental castings

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ABSTRACT

Objectives. The purpose of this study was to compare torsional strength, ductility and fracture behaviors of Ti–6Al–7Nb, CP Ti and Co–Cr alloy castings after laser welding.

Methods. Dumbbell-shaped castings of three metal alloys (Ti–6Al–7Nb alloy, CP Ti, Co–Cr alloy) were cut in half and laser welded with a Nd:YAG pulse laser-welding machine at either 220 V or 260 V of laser voltage. After being laser welded, all cast specimens were tested with a multi-axial hydraulic testing machine (MTS 858 Mini Bionix®) using a torsional test. The fracture surfaces were investigated with a scanning electron microscope.

Results. None of the laser-welded Ti–6Al–7Nb alloy and CP Ti castings was broken within the welded joint, showing torsional strength as high as the unwelded castings. Unlike the other groups, the laser-welded Co–Cr alloy castings exhibited brittle fracture appearance and provided substantially less torsional strength.

Significance. The torsional strength of the laser-welded Ti–6Al–7Nb alloy and CP Ti castings was as high as that of the unwelded castings while this finding could not apply to the Co–Cr alloy castings. This indicates that the mechanical strength of the laser-welded Ti–6Al–7Nb alloy dental casting is sufficient for clinical applications.

1. Introduction

The applications of commercially pure titanium (CP Ti) and titanium alloys used in medical and dental fields have dramatically increased over the last few decades due to their advantageous properties. For dental applications, many aspects of CP Ti and Ti alloys have been investigated in both clinical and laboratory studies [1–7]. Recently, Ti–6Al–7Nb alloy was introduced as an alternative dental casting material to CP Ti or Ti–6Al–4V alloy, not only because of some drawbacks of the mechanical properties of CP Ti used for some dental prostheses [3], but also because of the superior corrosion resistance of Ti–6Al–7Nb alloy when compared to others [4,8]. However, the reactivity and corrosion resistance of these metals are key

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in making dental practitioners and technicians avoid using the soldering technique to join titanium dental prostheses, as the disadvantages of doing so have been well pointed out [9–11]. Instead of the conventional way, laser welding became well accepted as being able to produce a precision welded joint with a narrow heat-affected zone and subsequently less distortion [12,13]. It has led to wide studies of using laser welding on these metals [12,14–19]. Even though several studies showed that the mechanical strength of laser-welded CP Ti or Ti alloys were at least as high as that of unwelded ones [16,20–23], most of them appeared to focus on the tensile property of the laser-welded joint. Very few have studied the torsional property [24], which is also one of the important mechanical properties for the use of dental materials. Considering that the dental prostheses are subjected to different directions of stress during function, more understanding on the mechanical properties of laser-welded CP Ti or Ti alloys in the aspect of torsional stress is necessary. Therefore, this study was aimed at investigating the torsional performance and fracture characteristics of laser-welded joints of Ti–6Al–7Nb alloy castings at two different voltages compared to CP Titanium and Co–Cr alloy dental castings.

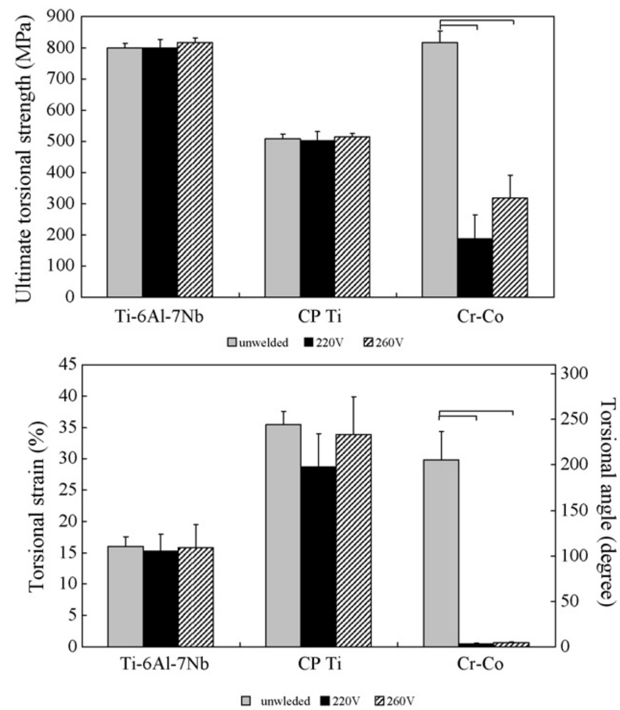


Fig. 1 – Means and standard deviations of ultimate torsional strength and torsional strain of laser-welded and control groups of three alloy (Ti–6Al–7Nb, CP Ti, and Co–Cr) castings. Connecting lines above the bars indicate statistically significant difference ($p < 0.05$).

2. Materials and methods

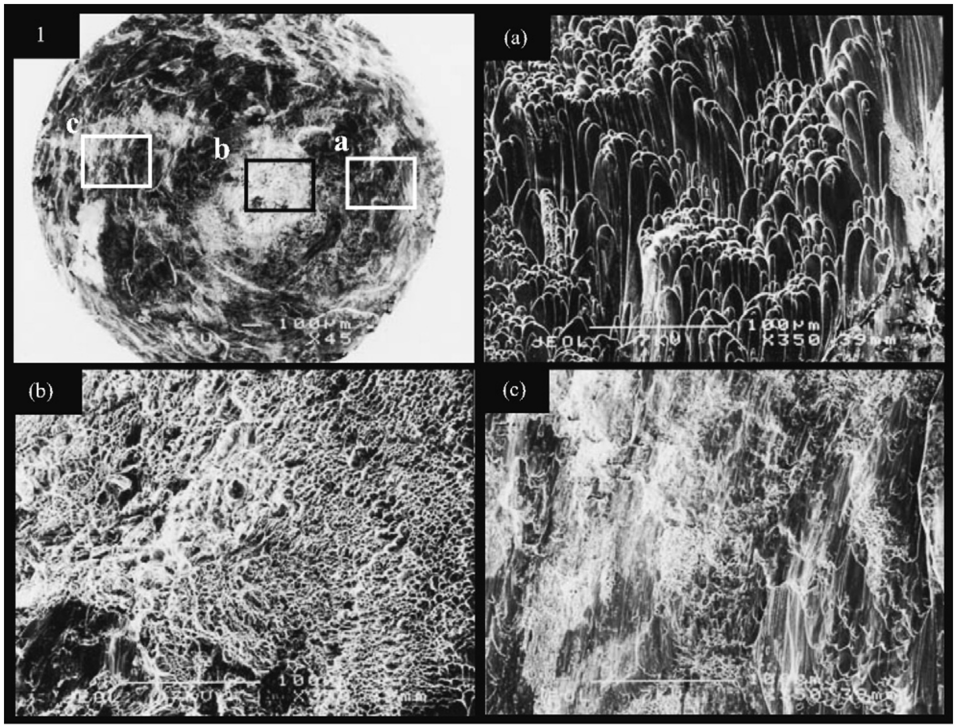
Ti–6Al–7Nb alloy (T-Alloy Tough, GC, Japan), grade 2 CP Ti (TITAN INGOT JS2, Selec, Japan), and Co–Cr alloy (Cobaltan Clasp, Shofu, Japan) were used to fabricate ISO 6871 dumbbell-shaped specimens, 18 mm in gauge length and 3 mm in diameter at the parallel part, according to the manufacturer's instruction. Ti–6Al–7Nb alloy and CP Ti specimens were cast in a magnesia-based investment (Selevest® CB, Selec, Japan) with an argon gas centrifugal casting machine (Ticast Super R, Selec, Japan), whereas Co–Cr alloy specimens were cast in a phosphate-bonded investment (Wiroplus®N, Bego, Germany) with a centrifugal casting machine (Denko Auto Sensor MD-201, Denko, Japan). Five specimens of each casting metal were prepared for each laser-welding condition group including the unwelded control groups. All specimens were inspected with a non-destructive X-ray instrument (DCX-100, Asahi Roentogen, Japan) to detect any noticeable internal defects. Specimens for laser welding were then cut at the parallel part with a 0.5-mm thick cutting wheel under water coolant. A group of five specimens of each metal was laser welded at either 220 V or 260 V of laser voltage using a Nd:YAG laser-welding machine (Alpha Laser ALP 50S, Yasui, Japan) under an argon gas atmosphere. The considerations of choosing these two laser voltages and the details of the other laser parameters, including the technique of performing laser welding, are explained in a previously published study [19].

All laser-welded specimens, including both the 220 V and 260 V of laser-welding conditions and the unwelded control groups, were later tested with a multi-axial hydraulic testing machine (MTS 858 Mini Bionix®, MN, USA). Torsional loading moment was applied with a crosshead speed of 0.1 degree/s. Torsional strength and strain were calculated with the cross-sectional area and gauge length of the specimen. The data was statistically analyzed by ANOVA and Tamhane's T2 test at 95% of significance level. The fracture surfaces from all experimental groups, including both laser-welded and unwelded groups after the torsional test, were observed by means of a scanning electron microscope (JSM-6400, JEOL, Japan).

3. Results

The results of the ultimate torsional strength and strain of both the laser-welded and the unwelded control castings are shown in Fig. 1. The ultimate torsional strength and strain were calculated with the cross-sectional area and gauge length of the specimen at the maximum value of torque. Except for the laser-welded Co–Cr alloy castings, it was found that both 220 V and 260 V laser-welded joints of the Ti–6Al–7Nb alloy and CP Ti castings provided ultimate torsional strength as high as the unwelded castings. A similar tendency was observed in the results of torsional strain of the laser-welded Ti–6Al–7Nb alloy castings. However, although the ultimate torsional strength of both groups of laser-welded CP Ti castings was comparable to that of the unwelded castings, torsional strain of the 220 V laser-welded CP Ti castings was noticeably lower than that of the other two groups with no statistically significant difference.

Regardless of laser voltage, all laser-welded Co–Cr alloy castings were abruptly fractured within the welded joints presenting considerably lower ultimate torsional strength and strain than those of the unwelded Co–Cr alloy castings ($p < 0.05$). Additionally, in this investigation it was found that both ultimate torsional strength and strain of the laser-welded



[×45: — 100 μm ; ×350: ———— 100 μm]

Fig. 2 – Fractographs of 220 V laser-welded Ti–6Al–7Nb alloy specimen fractured outside the welded joint. Micrographs (a–c) are higher-magnification views (×350) of the boxes in micrograph 1 (×45); (a) elongated dimples, (b) final ductile fracture (equiaxed dimples) and (c) abraded surface.

Co–Cr alloy castings were unlikely to be affected by the increase in laser voltage.

All of the laser-welded Ti–6Al–7Nb alloy and CP Ti castings were broken outside the welded joints showing ductile fracture surfaces observed by a scanning electron microscope (SEM) in Figs. 2 and 3, respectively; whereas all laser-welded Co–Cr alloy castings were abruptly broken within the welded joints as shown in Fig. 5. Micrographs (a) from Figs. 2–4 display shear dimple of fracture characteristics, especially the fracture surface of the Ti–6Al–7Nb alloy casting showing typical shear dimple of parabolic shape. In Figs. 2–4, micrographs (b) exhibit the final ductile fracture while micrographs (c) exhibit the abraded surfaces of each metal being the result of friction between the two broken ends during testing.

Unlike the ductile fracture characteristics of the unwelded Co–Cr alloy castings, the laser-welded Co–Cr alloy castings were fractured showing sharply defined plane and angles demonstrating the brittle fracture characteristics, regardless of laser-voltage (micrographs (a and b) in Fig. 5).

4. Discussion

Recently, laser welding has been increasingly utilized to construct dental prostheses among dental practitioners and dental technicians [25–32]. This is attributed not only to the advantages of laser welding including a lesser possibility of distortion due to a narrow heat-affected zone (HAZ), but also to the increasing use of CP Ti or titanium alloys for up-to-date dental treatments. CP Ti and Ti alloy dental castings have become an alternative to conventional gold alloy dental castings because of the advantages of lower cost and excellent properties. Among titanium alloys, Ti–6Al–7Nb alloy was developed in order to replace the controversial cytotoxic effect of vanadium in Ti–6Al–4V alloy. Although Ti–6Al–7Nb alloy has slightly lower mechanical strength than Ti–6Al–4V alloy, it provides better percent elongation and corrosion resistance [33]. Unfortunately, when joining of CP Ti and Ti alloys is required the soldering technique is not recommended as some disadvantages were reported, such as reduced mechanical strength [11]. Therefore, laser welding was introduced for use in not only joining the broken parts of titanium dental prostheses, but also fabricating large prostheses such as titanium frameworks for implant superstructures [29–32]. These dental prostheses would, nonetheless, be subjected to complex stress in various directions under oral function. Hence, the mechanical strength of laser-welded dental casting was evaluated by the means of torsional stress.

The previous study showed that the tensile strength of laser-welded Ti–6Al–7Nb alloy and CP Ti castings was as high as the unwelded same alloy castings when the joint thickness was completely laser welded [19]. Nevertheless, the same laser procedure could not be successfully employed in the Co–Cr alloy castings whose welded joints showed considerably low joint strength [19,34,35]. Similarly, it was found in this study that the joints of the Ti–6Al–7Nb alloy and CP Ti castings that were either completely (260 V) or peripherally (220 V) laser welded, provided no significant difference

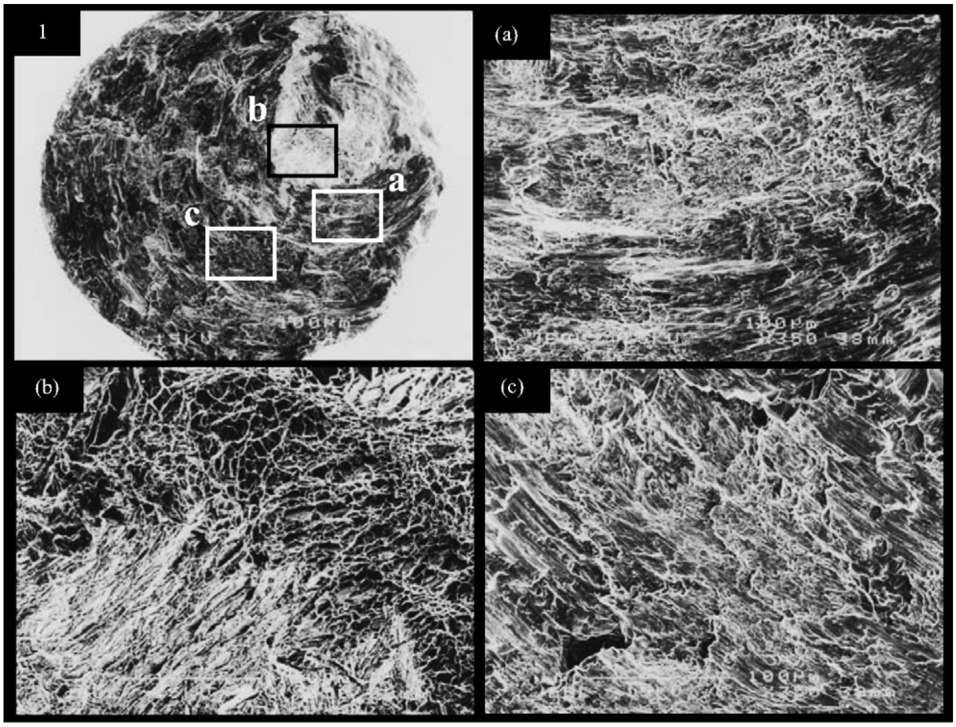


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Fig. 3 – Fractographs of 220 V laser-welded CP Ti specimen fractured outside the welded joint. Micrographs (a–c) are higher-magnification views (×350) of the boxes in micrograph 1 (×45); (a) elongated dimples, (b) final ductile fracture (equiaxed dimples) and (c) abraded surface.

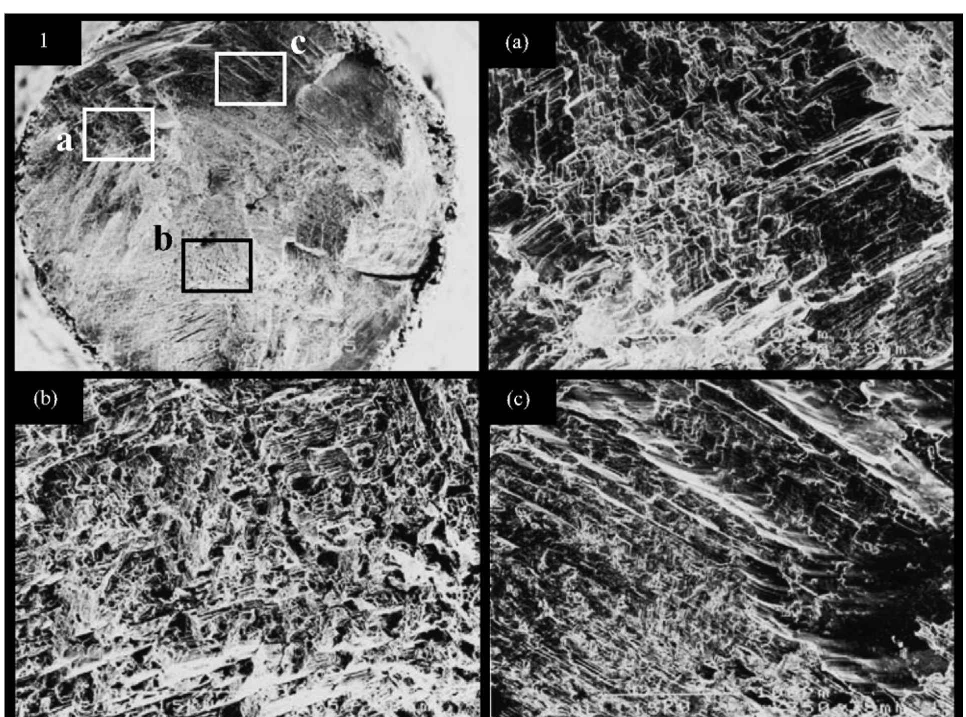

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Fig. 4 – Fractographs of unwelded Co–Cr alloy specimen. Micrographs (a–c) are higher-magnification views (×350) of the boxes in micrograph 1 (×45); (a) elongated dimples, (b) final ductile fracture (dimples) and (c) abraded surface.

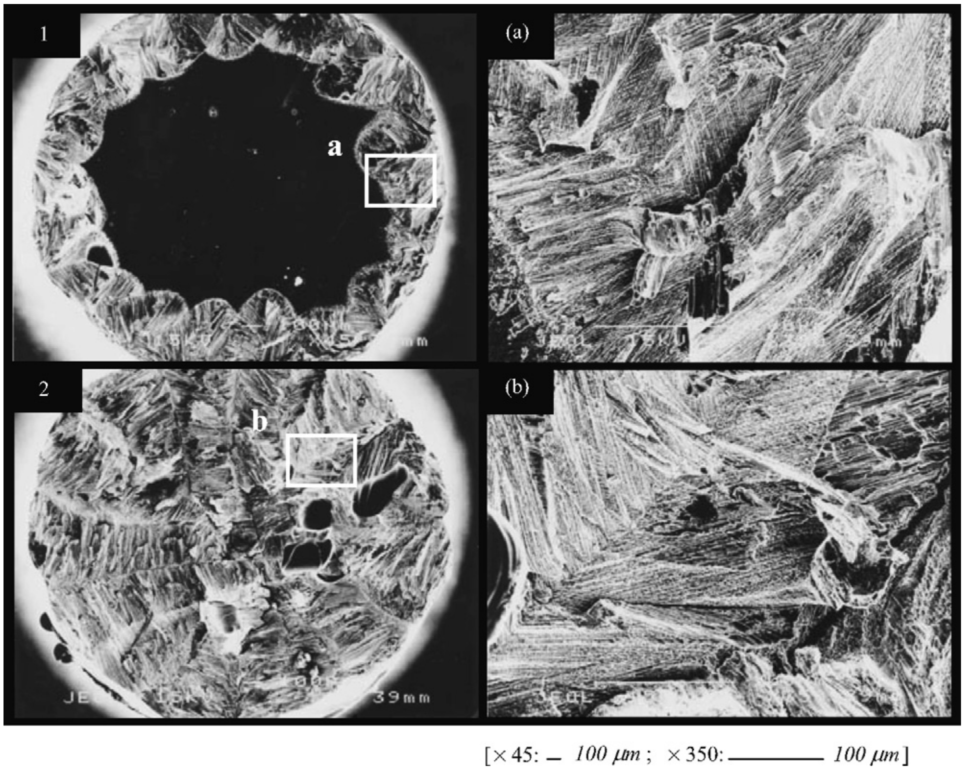

Fig. 5 – Fractographs of laser-welded Co–Cr alloy specimens (fractured within the welded joints): (1) 220 V and (2) 260 V. Higher magnification views (a and b: ×350) of the boxes in micrograph (1 and 2, respectively: ×45) showing cleavage fracture.

in terms of joint strength under torsional stress. Although the peripherally laser-welded joints of Ti–6Al–7Nb alloy and CP Ti castings could provide torsional strength as high as the unwelded or completely laser-welded castings, the 220 V laser-welded CP Ti alloy castings exhibited a noticeable decrease in torsional strain compared to the other experimental CP Ti groups with no significant difference. It is known that welding CP Ti or Ti alloys contributes to a decrease in the ductility of the fusion zone of the welded metals, which is a result of the microstructural changes after martensite transformation [36]. Not only rapid solidification of molten metals, but also high affinity for oxygen and impurities during welding, would lead to increased hardness and consequently to low ductility [12,13,16,37]. These factors are thought to be some of the main reasons for the reduced torsional strain in laser-welded castings.

In addition, it is of interest that the reduction in torsional strain of the laser-welded Ti–6Al–7Nb alloy castings was much smaller than that in the laser-welded CP Ti castings. It is distinguishable in the peripherally laser-welded castings. In fact, Ti–6Al–7Nb alloy possesses two phases (α and β phases) whose mechanical strength increases by strengthening mechanism unlike CP Ti which has one phase at a certain temperature. Additionally, in the pure state of titanium at a given temperature, α phase tends to be harder than β phase [38]. Therefore, both the transformed β microstructure in the fusion zone and a different phase ratios would affect the mechanical properties of both laser-welded metals [36]. These may explain the decrease and different reductions in torsional strain values between the laser-welded Ti–6Al–7Nb alloy and CP Ti castings.

Coinciding with the results of the tensile test [19], completely laser-welded Ti–6Al–7Nb alloy and CP Ti castings exhibited ultimate torsional strength and strain as high as the unwelded castings. In this study, regardless of laser voltage (220 and 260 V), all casting specimens of Ti–6Al–7Nb alloy and CP Ti were broken outside the welded joints with the ductile fracture characteristics shown in the SEM fractographs (Figs. 2a and 3a). Both Ti–6Al–7Nb alloy and CP Ti castings display the same characteristics of elongated shaped dimples in the direction of shear on the fracture surfaces, especially the Ti–6Al–7Nb alloy casting which shows a conspicuous parabolic shape, whereas final fracture of both metals shows a typical equiaxed dimple of final fracture (Figs. 2b and 3b). Since the friction occurring when two ends rubbed against each other could not be avoided in the torsional test, some damaged surfaces were observed (Figs. 2c and 3c).

In this investigation, whether the joints were completely or peripherally laser welded, all laser-welded Co–Cr alloy castings broke within welded joints. Markedly low ultimate torsional strength and strain of the laser-welded Co–Cr alloy castings compared to the unwelded castings were observed. Cracks occurred in the welded joints of all laser-welded Co–Cr alloy castings and several pores were also found in the welded area after being broken, which coincided with previous studies [19,35,39]. These defects are believed to be some of the main causes of abrupt fracture of laser-welded Co–Cr alloy castings. From fractographic examination, all laser-welded Co–Cr alloy castings were fractured indicating a cleavage pattern of brittle fracture characteristics (Fig. 5a and b). These findings were similar to those tested under tensile stress [19,35]. Unlike the laser-welded ones, the unwelded Co–Cr alloy castings were fractured exhibiting a typical elongated dimple of the final fracture (Fig. 4a). Even though one study indicated that laser welding provided higher joint strength of Co–Cr alloy than using electric brazing, the strength was still much lower than that of unwelded one, and this could be due to unfavorable microstructure changes leading to residual stress and plastic strain, in addition to grain growth, of the laser-welded joint [34]. Furthermore, one recent study has shown that an argon atmosphere used in the laser-welding technique could disturb the effective welding of this alloy [40]. Laser welding may not, therefore, be a reliable means of joining Co–Cr alloy.

The results in this investigation proved that with proper laser procedure, laser welding can be employed on Ti–6Al–7Nb alloy and CP Ti dental castings whose mechanical properties, including tensile strength, torsional strength and ductility are comparable to those of unwelded castings. Under present conditions, although the peripherally laser-welded Ti–6Al–7Nb alloy joints could tolerate the torsional stress before fracture outside the welded joints, they fractured within the welded joint under tensile stress [19]. Additionally, more reduced ductility was found in the peripherally laser-welded joints which fractured under tensile stress compared to ones tested under torsional stress. These findings clinically imply that peripheral laser welding is not suitable for clinical application due to the reduced mechanical strength of the welded joint. Although both completely and peripherally welded joints have high torsional strength, under multi-directions of occlusal loading, the failure of peripherally welded dental prostheses could be caused by multi-directional stresses including tensile stress and torsional stress.

5. Conclusions

Within the limitation of this study, the laser-welded Ti–6Al–7Nb alloy and CP Ti dental castings could provide torsional strength as high as the unwelded castings. The decrease in ductility was negligible when the welded joint thickness was completely laser welded. However, this high mechanical strength could not be successfully achieved on the laser-welded Co–Cr alloy dental castings in which the cracks and pores were unavoidably induced by the laser-welding procedure.

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