Laser Welding of Cast Titanium and Dental Alloys Using Argon Shielding

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Purpose: This study investigated the effect of argon gas shielding on the strengths of laser-welded cast Ti and Ti-6Al-7Nb and compared the results to those of two dental casting alloys.

Materials and Methods: Cast plates of Ti, Ti-6Al-7Nb, gold, and Co-Cr alloy were prepared. After polishing the surfaces to be welded, two plates were abutted and welded using Nd:YAG laser at a pulse duration of 10 ms, spot diameter of 1 mm, and voltage of 200 V. Five specimens were prepared for each metal by bilaterally welding them with three or five spots either with or without argon shielding. The failure load and percent elongation were measured at a crosshead speed of 1.0 mm/min.

Results: The factor of argon shielding significantly affected the failure load and elongation of the laser-welded specimens. The failure loads of argon-shielded laser-welded CP Ti and Ti-6Al-7Nb were greater compared with the failure loads of specimens welded without argon shielding for both three- and five-spot welding. Regardless of argon shielding, the failure loads of the laser-welded gold alloy were approximately half that of the control specimens. In contrast, the failure loads of the nonshielded laser-welded Co-Cr alloy were greater. The percent elongations positively correlated with the failure loads.

Conclusions: The use of argon shielding is necessary for effective laser-welding of CP Ti and Ti-6Al-7Nb but not for gold and Co-Cr alloy.

J Prosthodont 2006;15:102-107.

INDEX WORDS: laser, mechanical properties, titanium, titanium alloy, dental alloys

LASER WELDING is an advantageous method of connecting or repairing metal prosthetic frameworks because there are fewer effects of heating on the area surrounding the spot to be welded, and no further procedures, such as those used for conventional soldering, are necessary. With a laser-welding machine, it is possible to repair the frameworks with combustible acrylic denture base resins and artificial composite teeth, which would be burned by conventional soldering. Laser welding has been increasingly applied for fabricating the metal frameworks of prostheses[1,2] and for other procedures, such as recovering the metal ridge and cusp, blocking holes on the occlusal surfaces after excess occlusal adjustment, thickening the metal framework, or adding contact points after excess grinding and adjusting of the crown margins.

Cast titanium restorations have been clinically applied to an increasing number of patients, particularly those with allergies to other dental alloys, because titanium and its alloys possess excellent biocompatibility. However, titanium is characteristically difficult to cast and solder due to its high melting point and its strong affinity with gases such as oxygen, hydrogen, and nitrogen.[3,4] The high reactivity of titanium with gases results in the formation of hard and brittle structures due to the diffusion of the interstitial oxygen through the titanium lattice during the melting/solidification process. Therefore, it is necessary to use special equipment to cast or solder titanium frameworks. To connect cast titanium and its alloys, infrared soldering and laser welding are commonly employed methods. Laser welding is suitable to weld titanium and its alloys because they have higher rates of laser beam absorption and lower thermal conductivity than do dental casting alloys such as gold alloy;[5] however, due to the strong reactivity of molten titanium with oxygen in ambient air,

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Accepted December 22, 2004.

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1059-941X/06

doi: 10.1111/j.1532-849X.2006.00082.x

Table 1. Metals Used

Metal	*Product*	*Composition*	*Manufacturer*
CP Ti	ASTM grade 2	C: 0.02%, H: 0.0019%, O: 0.16%	Titanium Ind., Grand Prairie, TX
Ti-6Al-7Nb	T-alloy tough	Ti: 87%, Al: 6%, Nb: 7%	GC Corp., Tokyo, Japan
Gold alloy	Ney-oro 60	Au: 56%, Ag: 19.9%, Cu: 17%, Pd: 4%, Zn: 3%	Degussa-Ney Inc., Bloomfield, CT
Co-Cr alloy	Vitallium	Co: 60.6%, Cr: 31.5%, Mo: 6%	Austenal, Chicago, IL

the incorporation of oxygen during laser welding may affect the joint strength. Among the previous studies investigating the laser welding of titanium,[5-14] a few studies investigated the tensile[7] and bending[8] strengths using argon shielding in the chamber of the laser-welding machine. These studies reported that laser welding in the argon atmosphere affected the tensile and bending strengths of the laser-welded titanium, depending on the intensity of the laser irradiation; however, not many studies have been conducted to investigate the effect of argon gas on the mechanical strengths of laser-welded titanium. The mechanical strength of a welded joint is important in terms of the longevity of prostheses since a weak joint can cause failure of the metal framework during habitual use.

This study investigated the effect of argon gas shielding on the laser-welded strengths of cast Ti and Ti-6Al-7Nb and compared the results to those of laser-welded cast dental alloys.

Materials and Methods

Preparation of Cast Plates

The commercially pure (CP) Ti, Ti-6Al-7Nb and two dental casting (gold and Co-Cr) alloys used in this study are listed in Table 1. Two types of wax plate patterns were prepared for the laser-welded (0.5 × 3.0 × 10 mm) and nonwelded (control) (0.5 × 3.0 × 20 mm) specimens. The plate patterns were invested in the molds and then cast with each metal. CP Ti and Ti-6Al-7Nb were cast with a magnesia-based investment material (Titavest CB, Selec Co., Osaka, Japan) in an arc melting centrifugal casting machine (Ticast Super R, Selec Co.). The gold alloy was cast conventionally using a broken-arm centrifugal casting unit (Kerr Centrifico, Kerr Manufacturing Corp., Romulus, MI) and a cristobalite investment (Cristobalite, Whip Mix Corp., Louisville, KY). The Co-Cr alloy was also cast conventionally using an induction melting centrifugal casting machine (Modular 4, CMP Industries Inc., Albany, NY) and a phosphate investment (V.R. Investment, Austenal, Chicago, IL). Each casting procedure followed the manufacturer's instructions. After casting, the molds were allowed to bench-cool to room temperature. The cast plates were then divested, air-abraded with 50-μm Al_2O_3 particles, and ultrasonically cleaned with acetone for 10 minutes.

Preparation of Laser-welded Specimens

After the 3.0 × 0.5 mm surfaces of the two plates (0.5 × 3.0 × 10 mm) were polished with No. 600 SiC paper, they were butted against one another using a jig. The assembled cast plates were then welded with an Nd:YAG laser (Neolaser L, Girrbach Dental Systems, Pforzheim, Germany) at a constant voltage of 200 V, pulse duration of 10 ms, and spot diameter of 1 mm. The laser welding conditions were determined by correlating the penetration depth of the laser into each metal as measured in a previous study[15] with the thickness of the specimens used in this study. The laser welding was performed with and without argon gas shielding, in which a flow of argon gas was directed near the surface of the abutted area from two nozzles set at an angle of 45° on both sides above the specimen. The distance between the spot to be welded and each nozzle was approximately 1 cm. The nonshielded specimens were laser-welded in ambient air without using argon shielding. Five specimens were welded bilaterally for each metal using either three or five laser spots (Fig 1).

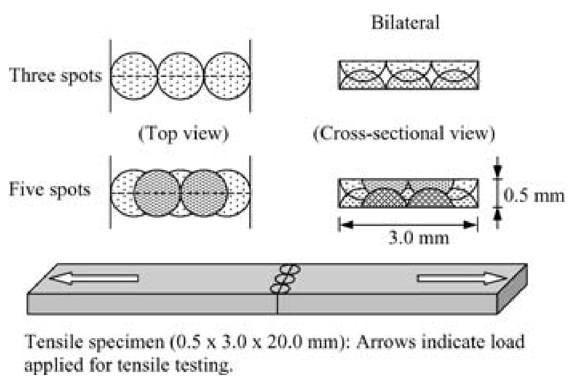

Figure 1. Laser welding configurations and tensile specimen used. Three or five laser spots were bilaterally applied perpendicular to the surface at the interface.

Tensile Testing

Tensile testing was conducted with a universal testing machine (Model 1125, Instron Corp., Canton, MA) at a crosshead speed of 1 mm/min and a gauge length of 10 mm (grips were attached 5 mm from both ends). Failure load (N) and elongation (%) were recorded, and the means (n = 5) and standard deviations were calculated. The data were statistically analyzed using analysis of variance (ANOVA) and Tukey's test at a significance level of $\alpha = 0.05$. After tensile testing, the fractured surfaces were examined using scanning electron microscopy (SEM) (JSM-6300, JEOL, Peabody, MA).

Results

The results of testing for failure load and elongation are presented in Figures 2 and 3, respectively. The factor of argon shielding had a significant effect on the failure load ($F = 193.89$, $p = 0.000$) and elongation ($F = 49.73$, $p = 0.000$) of the laser-welded specimens. Higher failure loads were obtained for laser-welded CP Ti and Ti-6Al-7Nb when argon shielding was used and were especially notable when the specimens were welded with five spots. They were nearly as strong as their corresponding control specimens (no significant difference; $p < 0.05$). Regardless of argon shielding, the failure loads of the laser-welded gold alloy were approximately half those of the control specimens. In contrast, the failure loads of the laser-welded Co-Cr alloy were greater for the non-argon shielded specimens. There were no statistical differences in the failure loads for the Co-Cr alloy between the control group and the nonshielded specimens welded with five spots. The percent elongation appeared to positively correlate with the failure load. The argon-shielded laser-welded CP Ti and Ti-6Al-7Nb had greater elongation. Regardless of the argon shielding, the elongation of the laser-welded gold alloy was less than half that of the control specimens. Higher elongation values were obtained for the nonshielded laser-welded Co-Cr alloy.

Figure 4 displays SEM micrographs of the fracture surfaces of CP Ti after tensile testing. The fracture surfaces of argon-shielded and the control specimens both evidenced some ductile fracture (Figs 4A and C). On the other hand, the fracture surfaces of the nonshielded specimens displayed brittle fracture (Fig 4B). The fracture mode of the Ti-6Al-7Nb specimens was similar to that of CP Ti, namely, the specimens welded with argon shielding (Fig 5A) and the control specimens (Fig 5C) underwent ductile fracture, while brittle fracture was found for the nonshielded specimens (Fig 5B). Figure 6 shows the fractured surfaces of the gold alloy specimens. A number of pores were

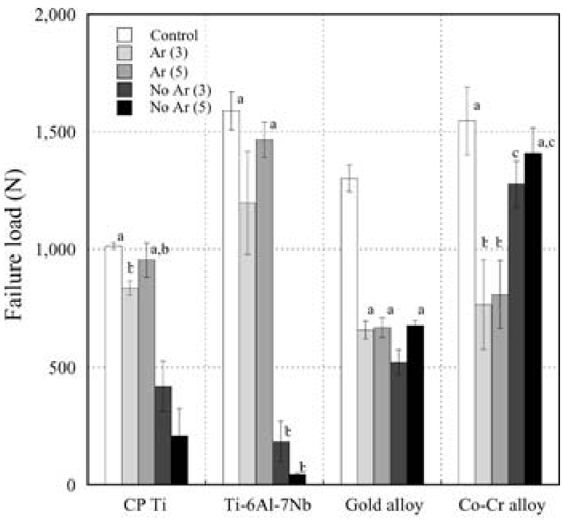

Figure 2. Failure load (N) of each alloy laser welded with three or five spots either with or without argon shielding. Identical letters indicate no significant differences ($p > 0.05$) in each alloy.

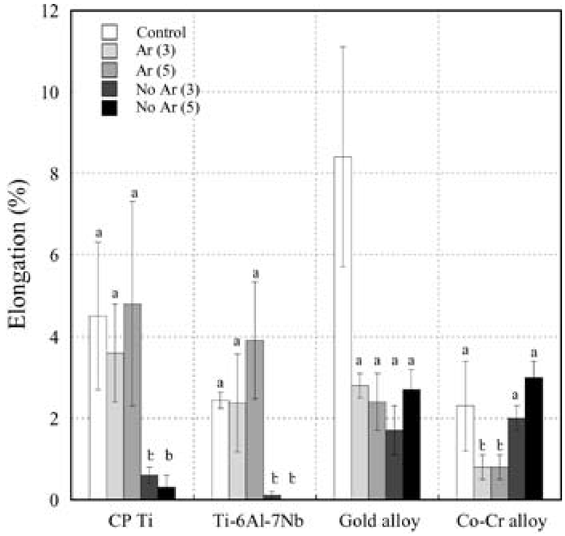

Figure 3. Elongation (%) of each alloy laser welded with three or five spots either with or without argon shielding. Identical letters indicate no significant differences ($p > 0.05$) in each alloy.

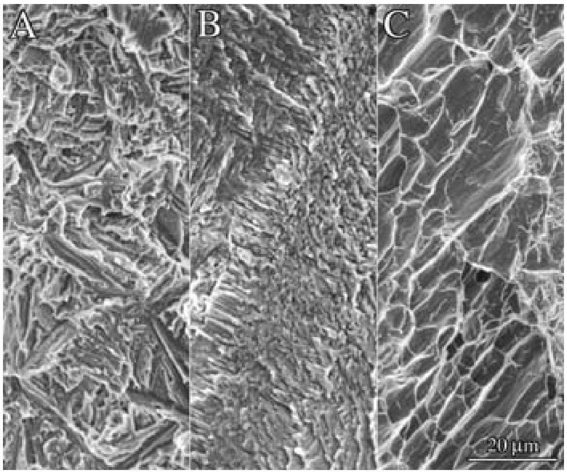

Figure 4. SEM micrographs of the fracture surfaces of CP Ti specimens. (*A*) laser welded with argon shielding; (*B*) laser welded without argon shielding; (*C*) control.

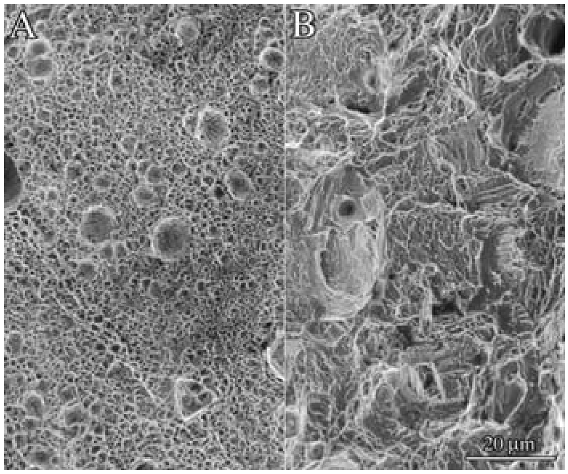

Figure 6. SEM micrographs of the fracture surfaces of gold alloy specimens. (*A*) laser welded without argon shielding; (*B*) control.

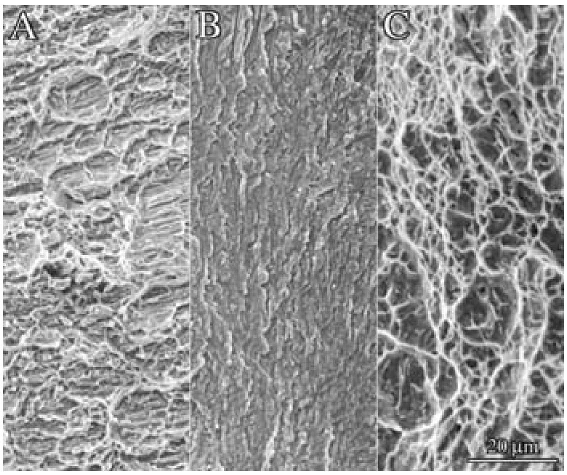

Figure 5. SEM micrographs of the fracture surfaces of Ti-6Al-7Nb specimens. (*A*) laser welded with argon shielding; (*B*) laser welded without argon shielding; (*C*) control.

observed on the laser-welded gold alloy specimens (Fig 6A), which demonstrated ductile dimple fractures, whereas the control gold alloy (Fig 6B) exhibited a mixture of ductile and brittle fractures. SEM photographs of the entire fracture surfaces of the Co-Cr alloy specimens are shown in Figure 7. Compared with the nonshielded specimens (Fig 7B), the shallower penetration by the laser was observed for the argon-shielded specimens (Fig 7A).

Discussion

Argon shielding had a significant effect on both the failure load and elongation of the laser-welded specimens. The argon-shielded laser-welded CP Ti and Ti-6Al-7Nb specimens had higher failure loads compared with those of the nonshielded specimens because of the incorporation of ambient oxygen into these alloys during the melting/solidification process of laser welding. Generally speaking, the incorporation of oxygen makes titanium extremely hard and brittle. The SEM observations of the fractured surfaces (Figs 4 and 5) of CP Ti and Ti-6Al-7Nb are consistent with their failure load and elongation results. Note the

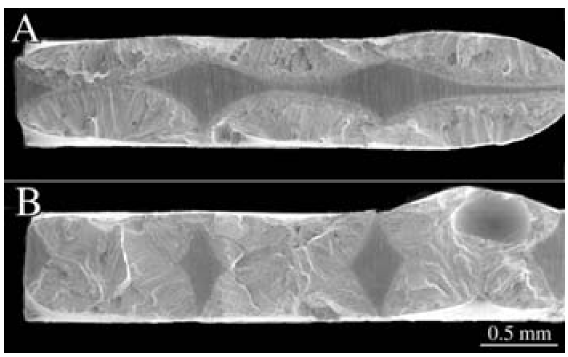

Figure 7. Representative SEM photographs of entire fracture surface (cross-section) for Co-Cr alloy specimens welded bilaterally with three spots. (*A*) with argon shielding; (*B*) without argon shielding.

brittle fracture of the laser-welded CP Ti (Fig 4B) and Ti-6Al-7Nb (Fig 5B) specimens without argon shielding. In previous studies that included tensile[6] and bending[7] tests, laser welding under argon atmosphere was reported to affect the tensile and bending strengths of the laser-welded titanium somewhat, depending on the intensity of the laser irradiation. On the other hand, apparent improvements took place in the present study in the tensile strength of the CP Ti and Ti-6Al-7Nb laser welded at a fixed laser intensity using argon shielding.

Although no pores were found in the nonwelded control gold alloy specimen (Fig 6B), a number of them were observed in the laser-welded specimens (Fig 6A). None could be seen in any of the laser-welded specimens for the other alloys. Considering the low vapor pressure of the zinc (boiling point: 907°C) contained in the alloy, these pores probably formed when the zinc vaporized during the high-temperature laser welding process. The low failure loads for the laser-welded gold alloy specimens could probably be attributed to these pores. Another reason for the low failure load of the laser-welded gold alloy specimen may be that the laser-welded portions are softened by quick solidification of the surrounding solid parent gold alloy, which has high thermal conductivity.[16] The surrounding solid gold alloy is likely to act as cold water does to quench the alloy during the solution (softening) heat treatment. Note the ductile dimple fractures in the laser-welded gold alloy (Fig 6A).

The depth of laser penetration was different in the laser-welded Co-Cr specimens with and without argon shielding (Fig 7) although the SEM micrographs indicated that the type of fracture was similar. The penetration depth into the argon-shielded specimen was shallower compared with the nonshielded specimen, probably because of the oxidation at the Co-Cr surface. No differences in penetration depth were found for the other alloys. The oxidation of the alloy surfaces is known to increase the rate of laser energy absorption.[17] The higher strengths of the specimens laser welded without argon shielding apparently resulted from increased penetration and an increased bonding area. The oxidation of titanium takes place over the entire melting area, whereas the oxidation of Co-Cr is limited to the surface, which increases the penetration of the laser into the alloy. In this study, a lower voltage and a wider spot were employed to weld about half of the specimen thickness (0.5 mm). If a higher voltage and narrower spot were used to produce a keyhole-like deep penetration welding to connect thicker alloys, the difference in the penetration observed between the Co-Cr alloy welded with and without argon shielding might not occur, due to its higher laser energy.

Clinically, the results obtained in the present study indicate that if cast pure titanium and Ti-6Al-Nb metal frameworks for prostheses are joined by laser welding under appropriate conditions in conjunction with argon gas shielding, these metal frameworks will have mechanical strength equivalent to that of the nonwelded one-piece cast metal frameworks. However, the laser-welded gold alloy metal framework may not be reliable for long-term usage, regardless of argon shielding, due to the pores created in the alloy. As for the Co-Cr alloy, the use of argon shielding may disturb the effective welding of Co-Cr frameworks under conditions similar to those used in this study.

Conclusions

Under the limitations of this study, the following conclusions can be drawn:

1. The results indicated that argon shielding is definitely necessary when laser-welding CP Ti and Ti-6Al-7Nb.
2. Regardless of the argon gas shielding, the failure load for the laser-welded gold alloy was half that of the control specimens because of the pores created during the welding process.
3. Argon shielding was found to be detrimental to effective welding of Co-Cr alloy under the conditions used in this study.

Acknowledgments

This study was supported in part by NIH/NIDCR grant DE 07188 and by grant Y2001-Z from the Baylor College of Dentistry Faculty Intramural Grant Program. Editorial assistance by Mrs. Jeanne Santa Cruz is also appreciated.

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