Effect of welding voltage on the mechanical behavior of a laser-welded cast titanium joint for dental prosthesis

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Titanium (Ti) has been widely applied to dental prostheses because of its excellent biocompatibility and mechanical properties. Dental clinical experiences have shown that the accuracy of the final Ti prosthesis suffers from some inevitable errors during the fabrication processes such as inaccurate impression, distortion of wax patterns, and bending resulting from metal constriction during the casting of multi-units crown and bridge. Therefore, dental technicians have often tried to make up for these errors by cutting and welding (re-connecting) the prostheses. Among many welding techniques, laser welding under inert environment is commonly used for re-connection of Ti prostheses.

The research of Qi *et al.* [1] found that there are fine acicular structures in the Ti weld metal different from the parent metal structure after laser welding. On the other hand, Wiskott *et al.* [2] found that the texture of equiaxed grains of weld metal is similar to the structure of surrounding Ti parent metal after laser welding. In terms of tensile strength, the study of Chai and Chou [3] showed that the strength of Ti weld metal is superior to the parent metal after laser welding. In contrast, Wiskott *et al.* [4] found that the tensile strength of weld metal of a laser-welded Ti joint is inferior to the parent metal. Furthermore, owing to the fusion of impurities, formation of martensitic structure, or coarsening of the crystal grains during the laser welding process, the Ti weld metal may become brittle [5, 6]. However, under proper welding conditions, the weld metal would not become brittle or lose its good elasticity during the laser welding process [3]. It is obvious that there is no agreement among the above studies owing to different welding parameters used, which resulted in discrepancies of the weld metal structures and consequent changes in the mechanical properties of the weld metal. In this study, we assayed the effect of welding voltage on the mechanical properties, including microhardness, breaking susceptibility, and breaking strength, of laser-welded cast Ti joints.

A Ti casting machine was used to produce commercially pure Ti plates (grade 2) 30 mm × 5 mm × 2 mm in size. Each cast Ti plate was cut into two even pieces by a fine cutting machine in a direction perpendicular to the long edge of the metal plate. The two pieces of Ti plates with uniform length were put together on the platform in the Nd:YAG laser welding machine. The laser beam was aimed perpendicular to the metal plate under an argon gas environment. A laser beam of 0.8 mm in diameter and pulse duration of 10 ms were chosen in this study. Various welding voltages, including 300, 310, 320, 340, 360, and 400 V, were used for welding. During the welding process, the mid-points of the four sides of the metal pieces were spot-welded first. The process was followed by spot welding with 1/2 overlap on the previous welding spot successively until the entire circumference was encircled. Fig. 1 shows the schematic diagram of the laser-welded cast Ti joint.

For microstructure observation, the side section of the laser-welded cast Ti joint (refer to Fig. 1) was ground with SiC paper to #1500, and then polished by 1 μm Al_2O_3 powder. The microstructure of the weld metal was observed using a light microscope after the polished surface was acid etched by a solution of $H_2O_2/HNO_3/HF/H_2O$ ($3 \times 3 \times 1 \times 3$ in volume) for 5 s.

For microhardness measurement, the polished Ti joint specimens were prepared in the same way as for the microstructure observation mentioned above. The average microhardness (Hv) of weld metal was measured under 100 g of loading for 20 s. During microhardness testing, 5–10 points were measured from the surface of the weld metal inward and an average taken. The distance between these points was 50 μm.

For the evaluation of the breaking susceptibility and strength of the weld metal, the four-point bending test was conducted on the laser-welded cast Ti joint using a universal testing machine with a crosshead speed of 0.5 mm/min ($n = 5$). The weld metal of the laser-welded cast Ti joint was located between the inner supports of the loading unit and experienced a uniform longitudinal tensile stress during the four-point bending test [7]. The bending test was carried on until the specimen broke. If the specimen did not break when the displacement of the loading rod reached 2 mm, the bending test was discontinued. The breaking strength was calculated as the ratio of breaking load to welding area on the breaking cross-section of the Ti joint. The fracture morphology of the Ti joint after the bending test was observed using a scanning electron microscope (SEM).

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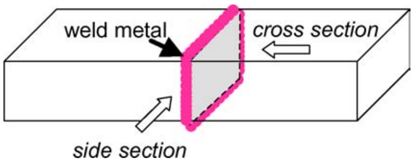

Figure 1 Schematic diagram of the laser-welded cast Ti joint.

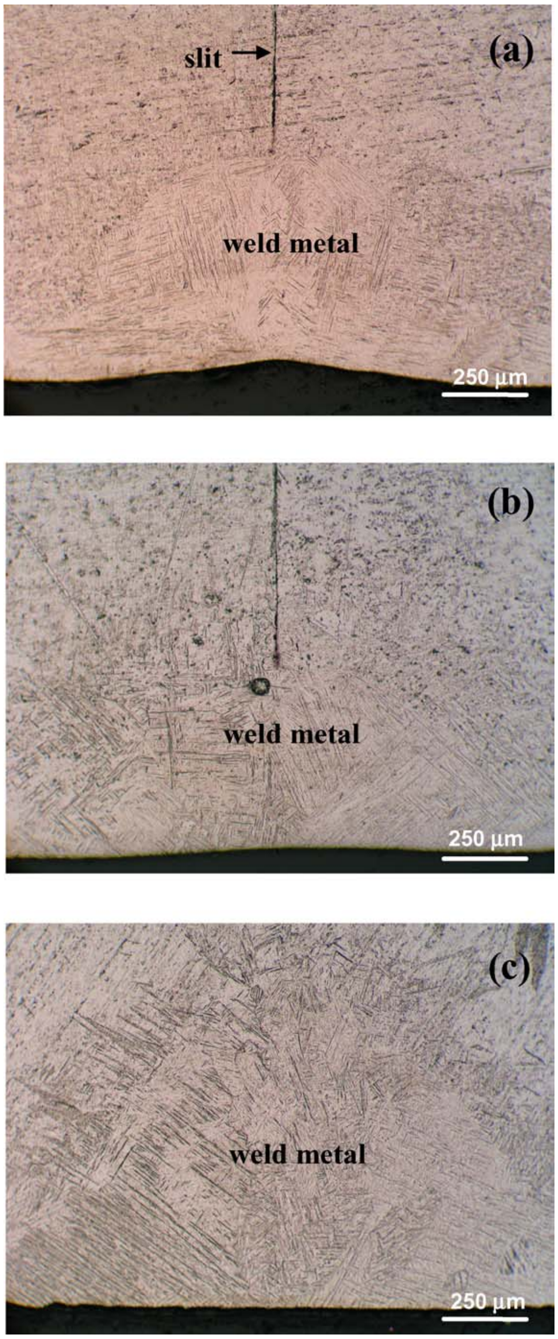

Figure 2 Optical micrographs of the weld metal of the laser-welded cast Ti joint with different welding voltages ((a) 300 V; (b) 320 V; (c) 360 V).

Fig. 2 shows the microstructure of the weld metal with different welding voltages ((a) 300 V; (b) 320 V; (c) 360 V). It illustrates that the weld metal had a uniform lamellar/acicular structure which became coarsen when the welding voltage increased. Furthermore, the laser welding process did not create a significant heat-affected zone (HAZ) in the neighborhood of the joint. It has been reported that laser welding is a fast process with quasi-instantaneous heating and cooling of the metal (up to 10^5 □/s) [8], hence basically no significant HAZ is formed. Similar results have been reported previously [2, 9].

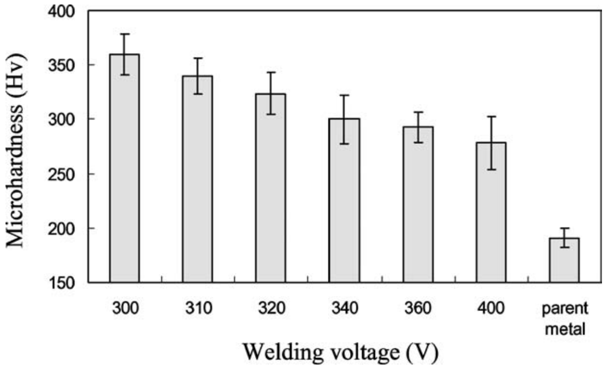

Figure 3 Average microhardness (Hv) of the weld metal of the laser-welded cast Ti joint as a function of welding voltage.

Fig. 3 shows the average microhardness (Hv) of the weld metal as a function of welding voltage (300–400 V). It reveals that the average microhardness of weld metal decreased on increasing the welding voltage (from 360 ± 18.72 Hv at 400 V to 278 ± 24.34 Hv at 300 V), but it was still much higher than that of Ti parent metal (190 ± 8.765 Hv). The decrease in the microhardness of Ti weld metal is believed to be related to the coarsening of the lamellar/acicular structure in the weld metal. It should be noted that all the values of microhardness in the same weld metal were independent of the location. This was ascribed to the uniform microstructure in the weld metal as shown in Fig. 2. Wiskott *et al*. [4] found that the hardness of Ti parent metal to be 192 ± 8.3 Hv. Laser welding can increase the joint's hardness to 267 ± 29.6 Hv. In this study, the mean increase in microhardness of Ti weld metal was between 88 and 170 Hv with respect to the Ti parent metal.

Table I shows the ratio of the breaking number to the testing number of laser-welded cast Ti joint as a function of welding voltage after four-point bend testing. During the bending test, the breaking of the Ti joint only occurred in the weld metal, namely the joint region, if breaking happened at all. It should be noted that 20 and 60% of the tested Ti joints with a welding voltage of 320 and 340 V, respectively, did not break during the bending test. Furthermore, no breaking occurred when the welding voltage increased up to 360 V. In other words, the breaking susceptibility of the Ti joint decreased with an increase in welding voltage. One of the reasons was due to the fact that a larger welding region, produced at a higher welding voltage, led to a lower tendency to fracture. When the welding regions at both the top and bottom sides of the Ti joint plate specimen interact with each other, it is likely that no breaking will occur during the bending test. This

TABLE I Ratio of the breaking number to the testing number of laser-welded cast Ti joint as a function of welding voltage after four-point bend testing

Welding voltage (V)	300	310	320	340	360	400
Breaking no./testing no.	5/5	5/5	4/5	2/5	0/5	0/5

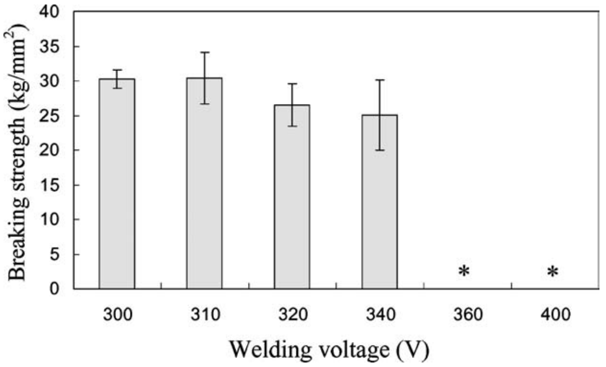

Figure 4 Breaking strength of the weld metal of the laser-welded cast Ti joint as a function of welding voltage after four-point bend testing (*: no breaking).

explains the fact that no breaking was observed for the specimens with a welding voltage higher than 360 V.

Fig. 4 shows the breaking strength of the weld metal as a function of welding voltage after four-point bend testing. The breaking strength decreased slightly with increasing welding voltage. The study of Wiskott *et al.* [2, 10] showed that the presence of a fine acicular structure can provide the weld metal with higher breaking resistance. Therefore, the coarsening of the acicular microstructure with increasing welding voltage (Fig. 2) led to a slight decrease in the breaking strength though no breaking occurred at a voltage higher than 360 V due to the interaction between the welding regions at the top and bottom sides of the Ti joint plate.

Fig. 5 shows the SEM observations of the breaking surface, namely the cross section in Fig. 1, of the laser-welded cast Ti joint with a welding voltage of (a) 300 V and (b) 340 V after four-point bend testing. As mentioned earlier, under four-point bend testing, the laser-welded cast Ti joints all broke inside the weld metal if fracture occurred. The breaking morphology was essentially brittle, showing a cleavage pattern. Though increasing the welding voltage led to a decrease in the microhardness (Fig. 3), a brittle fracture type still existed on the fracture surface for the Ti joint with higher welding voltage (Fig. 5b). Furthermore, some larger pores (around 50–120 μm in diameter) were observed along the welding fusion line of the weld metal in the case of the higher welding voltage. Berg *et al.* [5] found that the presence of large pores (around 100 μm in diameter) in the weld metal appears to be the most significant factor in controlling the strength of the laser-welded Ti joint. However, in this study, the presence of large pores (>50 μm in diameter) in the weld metal with a higher welding voltage seemed to have no

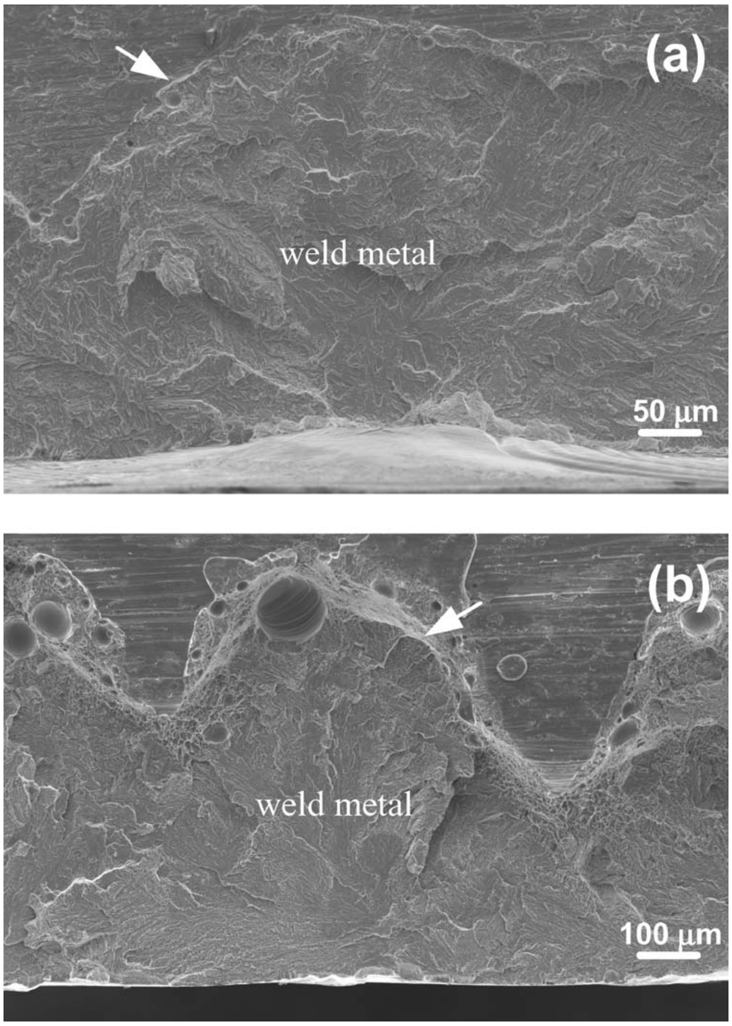

Figure 5 SEM observations of the breaking surface of the laser-welded cast Ti joint with a welding voltage of (a) 300 V and (b) 340 V after four-point bend testing (arrow indicated the fusion line of the weld metal).

detrimental influence on the breaking susceptibility of the Ti joint.

For the welding voltage range chosen for this study (300–400 V), increasing the voltage led to a decrease in the microhardness, breaking strength, and breaking susceptibility of laser-welded Ti joints. No significant HAZ was observed in the vicinity of the Ti joint. The presence of large pores in the weld metal had no detrimental influence on the breaking susceptibility of the Ti joint.

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