Laser Welding of Titanium and Dental Precious Alloys

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The performance of laser welding of Ti and two dental precious alloys (Ag-Pd-Au, Au-Pt-Ag) was investigated by mechanical testing and microscopic observation, using butt joint as design. The laser irradiation was done using a commercial Nd:YAG dental laser-welding device in a single pulse mode with output currents 150, 200, 250, 300 A, spot diameters 0.6, 0.9, 1.2 mm, and pulse duration 10 ms. The average welding fracture strength of the dissimilar metals were 108.9 and 137.2 MPa for Ti and Ag-Pd-Au alloy, and Au-Pt-Ag alloy, respectively. The average welding fracture strength of the same metals were 594.9, 648.8 and 312.9 MPa for Ti, Ag-Pd-Au alloy and Au-Pt-Ag alloy. The hardness increased in weld zone, compared with the base metals. Penetration depths were affected by the welding conditions such as the output currents and spot diameters. The welding cracks and porosity were observed in microstructures of the welds. Mapping by EPMA showed the remarkable heterogeneity of the component metals concerned. The welding cracks, porosities and granular precipitates similar to metallic compounds in the weld zone were suggested as the cause for lower welding fracture strength in the dissimilar welds, compared with the similar metals.

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1. Introduction

Gordon and Smith first described the use of laser energy for joining dental casting alloys in 1970. They stated that the laser-welding technique is less time-consuming and produced more accurate and stronger joints for both fixed and removable partial prostheses. Preston and Reisbick compared the ultimate tensile strength of noble base metal, and mixed metal welds to conventional dental joining methods and found that “laser fusion is as good as, or better than, unions created by conventional dental joining methods”. Smith et al. stated that the laser welding of dental casting gold alloys is “metallurgically feasible” after an investigation of the weld properties and microstructure. The laser welding process was introduced into dentistry at the end of the 1980s. Joining technique of dental appliances was simplified by the development of welding machines. Metal prosthetic pieces are joined directly on a master cast of gypsum without placing in investment. The laser welding has an advantage to heat only limited areas for the bonding as a concentrated laser-light beam is applied. The laser welding is a kind of high-density energy welding and is generally suitable for welding non-precious alloys such as Co-Cr and Ni-Cr.

In recent years titanium and its alloys have been used to produce crowns, bridges, dentures and artificial roots because of their good biocompatibility, and outstanding mechanical properties. In addition, the progress of precise dental casting and joining methods of titanium has accelerated numerous applications development. In the case of ordinary soldering it is very difficult to bond titanium based materials because they are oxidized easily in air at high temperature. In order to solve the problem an infrared heating method was developed using an argon atmosphere and Ti-Ni-Cu solder. Laser welding of titanium with the dental casting has been also studied. Laser welding is effective for joining titanium because the procedure is easier than the dental soldering. Though the dental casting of titanium is continuously improved, defects are often present in cast titanium. Cast titanium meant to clasp the dentures are liable to break due to the defects. If the cast titanium denture plates can be joined to cast or wrought clasps made of dental precious alloys such as Ag-Pd-Au alloy and Au-Pt-Ag alloy by laser welding, different designs of the dentures would be possible. However, no systematic research was carried out on the laser welding of dissimilar metals like Ti and dental precious alloy.

The commercial dental laser welding device used by us has three operating parameters that can be set: output current, spot diameter and irradiation time. In order to clarify the problems of laser welding of Ti and the dental precious alloys, the objective of this study was to investigate laser welding between Ti and Ag-Pd-Au, Au-Pt-Ag alloys with different operating parameters. The tensile fracture strength, hardness and microstructures of the welds were examined.

2. Materials and Methods

2.1 Preparation of test specimens

Materials used are shown in Table 1. The wrought metal
bars have 3.0 mm in diameter and 30 mm in length. The laser welder used for the experiment is the dental laser welder (TLL7000PLUS, ADT, Tokyo, Japan). Weld areas were sandblasted with alumina (50 μm) at 0.2 MPa, and cleaned ultrasonically in detergent solution first then in pure water, and finally degreased with acetone. The bars were fixed in the jig shown in Fig. 1(a). Two pieces of Ti and precious alloy bar were placed in the jig to maintain the alignment of the bar throughout the joining procedures. A pulsed Nd:YAG laser unit was used for the welding operations, which were carried out in an argon atmosphere. The focus of the laser was set at the interface of the two bars. Laser welding shots were carried out on diagonal lines eight times while argon gas was blown as shown in Fig. 1(b). Output currents of the laser were 150, 200, 250 and 300 A. Spot diameters were 0.6, 0.9 and 1.2 mm. The pulse duration was fixedly 10 ms.

2.2 Measurement of fracture strength

The tensile test was carried out using universal test machine (Model 4202, Instron/C1 Japan, Tokyo, Japan) with cross head speed 1 mm/min and a gauge length of 20 mm. The test was done five times for each welding conditions. Cross section areas were calculated using original diameters of the metal bars.

2.3 Observation of fracture surfaces

The fracture surface of tensile specimens was observed macroscopically using a digital microscope (VH-6300, KEYENCE Co. Tokyo, Japan) at magnifications of 25 and details by a scanning electron microscope (S2380N, HITACHI Co. Tokyo, Japan).

2.4 Electron probe microanalyzer

Butt-welded specimens with different conditions were embedded in epoxy-resin using rubber moulds. After the resin set, the embedded specimens were stripped from the moulds. The specimens were ground to the half section to expose the weld zones using 600, 800 and 1000-grit Emery papers and polished by a lapping wheel with suspensions of alumina (2 micron, 1 micron). The polished surfaces were coated by evaporation of carbon for the electric conductivity. Mapping images of Ti, Au, Pt, Pd, Ag and Cu were obtained at the weld zones with an electron probe microanalyzer (EPMA) (JXA-8900, JEOL, Akishima, Japan). At the same time, reflection electron images were observed.  

2.5 Hardness test

Welded region hardness was measured by Vickers hardness tester (Type M, Shimadzu, Kyoto, Japan), using the same polished specimens as for the EPMA observation. The measurement area extends 1 mm from the weld on each bar of the joint. The measurements were done with 0.1 mm pitch, along the lines placed at 0, 0.5 and 1.0 mm below the section edge. The load was 200 g and loading times was 15 seconds.

3. Results

The fracture surfaces for Au-Pt-Ag alloy were shown in Fig. 2 for different spot diameters and output currents. The penetration depths reach the core of the bars when the output currents increased and the spot diameter decreased. For too big output currents and too small spot diameters, the metals are volatilized, and the penetration areas consequently decreased. The deep concave surface was formed in the weld zone by sputtering and under-fill for the 0.6 mm spot diameter.

Figure 3 shows the reflection electron micrographs of vertical cross section of the welded zone under the conditions that showed the largest fracture strength for the combinations of Ti and Au-Pt-Pd (a), Ag-Pd-Au alloys (b). In both micrographs, it was observed the contrast differences characteristic to reflection electrons. Centerline cracks and porosities were observed in both welds.

Figure 4 and Fig. 5 show the secondary electron images and elemental mapping images of the welded zones between Ti and Au-Pt-Ag, Ag-Pd-Au alloy, respectively. In the case...
of Au-Pt-Ag alloy, Ti and the alloy were soluble in the weld zone, but in some areas the concentration of Ti and the alloy showed the opposite distribution. In the case of Ag-Pd-Au alloy, Ti and the alloy were mutually mixed though the melted zone was not homogeneous. The alloy was relatively soluble in base Ti, while Ti partly melts in the alloy. Ag was uniformly distributed on the Ti side, but there were Ag rich phases with the higher concentration than the alloy.

Fractured surface of welds between the similar metals showing the largest fracture strength was presented in Fig. 6. The melted zones were not extended all over the weld except for Ag-Pd-Au alloy. The fracture surface shows the dimple pattern and porosity. Cup and cone pattern was observed in Fig. 7(b).

Fractured surface of welds between the similar metals showing the lowest fracture strength. A decrease of the weld zone was observed in Fig. 7(c), due to the alloy under-fill. Porosities and cracks were increased. Different phases of small granular particles were found near the crack in Fig. 7(d).

Figure 8 and Fig. 9 show the mean values and standard deviation of fracture strength of the welds as function of the output current and spot diameter. In both cases, the data for the spot diameters 0.6 mm and 0.9 mm at 300 A output current were omitted because of metal sputtering. The 0.6 mm spot diameter was not adopted for the same reason at 250 A output current. The highest average fracture strength (108.9 MPa) was obtained for Ag-Pd-Au alloy at 200 A and 1.2 mm spot diameter. On the other hand, using Au-Pt-Ag alloy, the highest average fracture strength was 137.2 MPa at 250 A output current and 1.2 mm spot diameter. At lower output current (150 A) the fracture strength decreased (107.4 MPa) for 0.6 mm spot diameter. With the exception of 200 A outputs current no uniform increase in the fracture strength were observed by the variation of the output current and the spot diameter.

Figure 10 presents the welding fracture strength based on the best data for different joint combinations. For the joints made of the similar alloy the welding fracture strength was
594.9 MPa for Ti, 648.8 MPa for Ag-Pd-Au alloy, and 312.9 MPa for Au-Pt-Ag alloy. The joints of different combinations of Ti and Ag-Pd-Au, Ti and Au-Pt-Ag showed the welding fracture strength lower than those of the similar alloy.

Figure 11 and Fig. 12 were the inside the welded zones shown in EPMA mappings of Figs. 4 and 5, respectively. The lines of a, b and c were Vickers hardness corresponding to cross section edge at surface, 0.5 mm below and 1.0 mm below the edge. Both for Ag-Pd-Au and Au-Pt-Ag alloys, the hardness were higher inside the welded zone and lower just out of the welded zone, heat-affected zones compared with base metals. The hardness in the welded zone was more or less uniform and the maximum hardness of welds was higher by 200 than with base metals in Au-Pt-Ag alloy (Fig. 12). In the Ag-Pd-Au alloy, hardness in the center right region was lower than the left region.

4. Discussion

4.1 Parameters affecting on weldability

The operating parameters of laser-welding machine and the physical properties of metal determine the weld strength. The operating parameters of welding machines are: pulse duration, maximum output, irradiation energy, output energy, irradiation frequency and laser spot diameter. The output current, pulse duration, and spot diameter are adjustable for most of the welding machines used in dentistry.

The following physical properties were considered: beam...
absorption ratio, thermal conductivity and melting temperature. Metals with high beam absorption ratio and low thermal conductivity are melted at low output energy levels. Slow heat dissipation due to the low thermal conductivity generates the deep penetration. As shown in Table 2, beam absorption ratios, and thermal conductivities present the remarkable difference for different metals. Ti, Pt and Pd have the high beam absorption ratio, and low thermal conductivity, thus the application of low energy laser welding is possible. In contrast Au, Ag and Cu need high laser energy due to their low beam absorption ratio and high thermal conductivity.

It is well known that different impurities, defects, surface roughness and oxide films affect the beam absorption ratio. In the present study all metal specimens were alumina sandblasted and degreased with acetone in order to improve their beam absorption ratio.

### 4.2 Thermoconductive and keyhole type melting

Laser welding induces either the thermoconductive or keyhole type melting of metal. At low irradiation energy the thermoconductive melting is predominant when penetration depth is small and metal is melted only at the surface. When high-energy laser concentrates the energy of several kW on a small spot, keyhole type melting is produce. During keyhole type melting important quantity of metal is evaporated. The tremendous generated heat combined with the intense metal evaporation generates the deep holes called keyholes, which are rapidly filled with molten metal as the irradiation cease and metal vapor pressure drops. In order to obtain the high weld strength, the perfect melting is needed in the center of weld zones, thus the keyhole type is recommended.

Analyzing the fracture surface of the weld of Ti and Au-Pt-Ag alloy the influence of the spot diameter on the penetration depth was assessed for low output energy. For output of 150 A and spot diameter 1.2 mm thermoconductive type with small penetration depth was observed (Fig. 2). In addition the un-melted regions are visible for output 150 A, spot diameter 0.9 mm, and output 200 A, spot diameter 1.2 mm (Fig. 2). Increasing the output energy and decreasing the spot diameter further, keyhole type predominates. However, molten metal loss caused by metal sputtering under high density beam irradiation generates the weld under-fill, especially at small spot diameters. This atypical under-fill decreases the actual melting area, and affects the weld strength (Fig. 9). Both melting types were also observed in the case of the welding between Ti and Ag-Pd-Au alloy.

### 4.3 Macrosegregation in the welds of dissimilar metals

Weld of dissimilar metals presents segregation at macroscopic scale called macrosegregation. According to Dr. Shindo, “A very important mechanism for macrosegregation is the convection of the solute-rich interdendritic liquid in the mushy zone of the solidifying ingot. This convection is caused by the gravity force and the shrinkage of the liquid metal during solidification. The dendritic structure in the weld mushy zone is much finer than in the ingot mushy zone. Macrosegregation due to convection in the weld mushy zone would be rather small.”

There are important differences between the beam absorption ratio, thermal conductivity and melting point of the used metals, thus their melting behavior is very different. One of the metals melts easily while the other one does not melt properly under the same laser irradiation conditions. The welding pool solidifies before the uniform mixing of metals because of the fast and premature solidification.

Figures 3a, b shows the reflection electron image of the weld zone, evidencing the presence of light and heavy elements due to the macrosegregation. EPMA analysis of the weld of Ti and Ag-Pd-Au alloy indicates that the precious metals are lumped inside the welding pool (Fig. 5), and there is a remarkable heterogeneous distribution of Au, Pd and Ag. Similar heterogeneous precious metal distribution was observed in the weld of Ti and Au-Pt-Ag alloy (Fig. 4). However the elemental distribution was more uniform than in the case of the Ti and Ag-Pd-Au alloy weld. The boundary between the base Ti and the solidified bead is more defined than that between the base precious alloys and the bead (Fig. 3). Ti melts faster than the precious metals due to its high beam absorption ratio and low thermal conductivity, thus the melting alloys distribute heterogeneously in the melted Ti.

### 4.4 Weld defects

The microscopic observation also showed the defects in the weld. The main weld defects are the crack and the porosity. The cracks are generated during or after welding, and are produced by overheating of the welding zone and the heat affected zone (HAZ). The crack in the weld zone is called solidification cracking and the crack in HAZ liquation crack. The solidification cracking is generated by contraction stress that arises in the welding and often occurs between intermetallic compounds in the welding pool of dissimilar metals. The liquation crack is generated by the contraction stress in the grain boundary of HAZ. At the weld zone of the dissimilar metals investigated, a center solidification cracking was observed (Fig. 3b).

The porosity is caused by the entrapment of bubbles of metal vapor, shielding gas and air in the solidifying metal, or the keyhole closure before it is filled by molten metals at the end of irradiation. Figs. 6(a, b, c) and Figs. 7(a, c) present the investigated welds porosity. Root porosity is also found in the lower weld-zone (Fig. 7c).

### 4.5 Welding strength

The weld strength is dependent on the laser irradiation parameters such as output energy, pulse duration, and spot diameter. The melting types have strong influence on the
fracture strength, and they are determined by the laser output and spot diameter (Fig. 2, Fig. 6, and Fig. 7). High irradiation energy produced cavities in the under filled regions also affects the weld strength. For the welds of Ti and Au-Pt-Ag alloy, the maximum fracture strength of 137.2 MPa was obtained at the laser output of 250 A and spot diameter of 1.2 mm, when in the keyhole-type welding pool, central non-melted regions and porosity were observed. The minimum fracture strength of 36.8 MPa was obtained at the laser output of 200 A, and the spot diameter of 0.6 mm. Large under-fill and porosity was observed. For the maximum fracture strength welds of Ti and Ag-Pd-Au alloy, the keyhole type melting and non-melted areas were observed. As shown below, due to the more uniform metal distribution and to the less weld cracks and porosity, the fracture strength of Ti and Au-Pt-Ag alloy weld is generally higher then for Ti and Ag-Pd-Au alloy weld.

4.6 Fracture surface and welding strength of similar and dissimilar combination

The maximum fracture strength of the weld between Ti and dental precious alloys is much lower than for the weld of the similar metals (Fig. 10), because of the higher defects occurrence (Fig. 3). The investigated welds between dissimilar metals showed 3 up to 6 times smaller maximum fracture strength then those for similar metals. Only a few weld cracks and little under-fill are observed in the welds of similar metals, although porosity and dimple pattern is present in the ductile fracture. The maximum fracture strength of the weld of similar metals is: 648.8 MPa for Ag-Pd-Au alloy at output 320 A, 312.9 MPa for Au-Pt-Ag alloy at output 300 A, and 594.9 MPa at output 200 A in Ti. Higher output energy is needed to form welding pool in dental precious alloys than in Ti, because of their low beam absorption ratio and high thermal conductivity (Table 2). Among the investigated metals, the Au-Pt-Ag alloy weld had the highest fracture strength, and the weld presents the extended porous structure with numerous non-melted areas (Fig. 6a).

The fractured surface morphology of dissimilar metal welds explains their fracture behavior. Deep penetration along with high porosity and dimple pattern is observed in the ductile fracture for the weld of Ti and Au-Pt-Ag alloy, weld with the highest fracture strength (Figs. 7a, b). Welds with the minimum fracture strength are regularly fractured in the welding pool area.

In this case numerous under-fills, weld cracks, and porosity are observed on the fracture surface (Fig. 7c). In addition, near the crack, intermetallic compound-like granular material was observed (Fig. 7d). It is well known that Ti forms intermetallic compounds with Au, Pt, Pd, Ag and Cu.18–22 These compounds could lower the weld strength between dissimilar metals.

The comparison between fracture strength in Figs. 8, 9 and observation of fracture surface of welds of Fig. 2 leads to the recognition of the tendency that the region, the conditions for relatively high welding strength situates on the diagonal from the lower left (low output current and small spot diameter) to the upper right (high output current and large spot diameter) of Fig. 2. In the lower right where high output current for small diameter cause too high beam density leading to the volatilization (keyhole type melting). In the upper left where low current for large diameter gives the insufficient beam density which produces the shallow welds (thermoconductive type melting). For both these conditions strength is low the welds are too weak to test.

4.7 Hardness distribution in the welds

The hardness test is an effective evaluation method of the metallurgical changes produced by welding. The hardness of the welding pool is higher by 200 units in the weld of Ti and Au-Pt-Ag alloy, respectively by 400 units in the weld of Ti and Ag-Pd-Au alloy than the hardness of the base metals. The hardness varies continuously along the transversal section of the weld (Fig. 11, Fig. 12). However this variation is less pronounced in the weld of Ti and Au-Pt-Ag alloy than of Ti and Ag-Pd-Au alloy. We suppose that metallurgical changes of the weld zone determine their hardness. The reflection electron images and the elemental mapping images of the welds evidenced the visual differences of the solidification patterns in both welds (Fig. 3, Fig. 4, and Fig. 5). Isolated points of high hardness observed in the welding pool may be produced by different phases of intermetallic compounds of Ti and the precious metals. Near the welding pool the hardness of the base metal is lower then normal, due to heat affected zone.

5. Conclusions

(1) Reflection electron image and EPMA mapping showed the remarkable heterogeneity of the components concerned.

(2) The welding cracks and porosities were observed in microstructures of the welds.

(3) The hardness increased in the weld zone compared with the base metals.

(4) The fracture strength of the dissimilar welds was much lower than that of the similar metals, mainly due to the cracks and pores formed in the weld zones, as a result of insufficient melting and mixture between components with different properties.

(5) The fracture strength in the dissimilar combinations was lower for the laser irradiation conditions to produce the weld of the thermoconductive type at larger diameter with low current which gives the too shallow welds due to the insufficient energy and that of the keyhole type at small diameter with high beam energy which causes the volatilization.

(6) The higher fracture strength was obtained in the intermediate conditions of these above of (5) and the condition for the highest load was situated with the higher current (200 A or 250 A) at large spot diameter (1.2 mm).

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