Original Article

A Basic Study on Laser Beam Welding of Titanium Plates Using an Nd:YAG Laser Welder with Pulse width Modulation

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Introduction

Titanium is not only a metal of choice for implants because of its excellent biocompatibility, it is also expected to be used for prostheses. However, we still have difficulty fabricating and repairing titanium prostheses using conventional casting and soldering. In recent years, commercial Nd: YAG laser welding...
machines for dental laboratory work have become available on a market, overcoming these difficulties.

On the other hand, we have already proposed numerically controlled combined machining of titanium, not only to reduce labor in laboratory work but also to fabricate prostheses of higher quality. Welding is a key technology to combine the separated parts fabricated in casting, mechanical machining, and electric discharging machining. However, laser beam welding is sensitive for controlling energy for application to precision prostheses.

In this study we remodeled the oscillating battery of a commercial laser welder, to control the welding energy using PWM, to obtain fundamental information on irradiating conditions related to the quantity and quality of penetration into titanium.

**Materials and methods**

A commercial Nd : YAG laser welding machine (TLL-7000; Tanaka, Italy) was remodeled by adding a control circuit of PWM (pulse width modulation), to convert the electric current of an Xe flash lamp for excitation at single pulse, from its original value to 66% at any time during the pulse duration. Figure 1 shows the laser-welding machine used in this study. Figure 2 shows both the original and modulated pulse waves.

JIS Grade 2 commercial titanium plates (KS50; Kobe Steel, Japan), of thickness 3 mm, were irradiated with a single pulse laser beam (Ψ = 0.3 mm) perpendicular to the surface, under an argon gas atmosphere (5 l/min). An irradiation spot was fixed to the focusing spot of the condensing lens equipped in the welding machine. The laser beam was irradiated with different energy conditions, shown in table 1 and figure 3, to evaluate the quantity and quality of penetration at the irradiation spot.

Titanium plates were sectioned on the center of the irradiation spot by wire electric discharge machining (LS350X; Japax, Japan). Specimens were embedded with resin, followed by polishing metallurgically. The sectioned surface of the irradiation spot was examined using a metallographical microscope (Versamet; Union Optical, Japan). Photographs taken with a 35mm film were scanned with a film scanner (Fotovix III S; Tamron, Japan) connected with a personal computer (DP5150; Compaq, USA).

The width and depth of penetration were evaluated on the picture elements of the data. The macroscopic surface and the internal structure of the irradiation spot were also examined on the picture.

**Results**

Figure 4 shows the scanned metallurgical structure...
Table 1 Laser beam conditions examined in this study

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Fundamental pulse</th>
<th>Additional pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tube current (A)</td>
<td>Pulse width (ms)</td>
</tr>
<tr>
<td>A</td>
<td>150-275</td>
<td>25 step</td>
</tr>
<tr>
<td>B</td>
<td>250</td>
<td>0.5, 1, 2, 4, 8, 15</td>
</tr>
<tr>
<td>C</td>
<td>275</td>
<td>4</td>
</tr>
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</table>

Figure 3 Experimental conditions of the single pulse investigated in this study

of the penetration. Figure 5 summarizes the width and depth of penetration at each condition.

Figures 4-A and 5-A show the results of penetration under the normal pulse condition of experiment A. The width and depth of penetration increased with an increase of the current (pulse height), and reached to a maximum at 225-250A, because of the increase of supplied energy. However, the width and depth of penetration were conversely decreased at 275A, because of the scattering of evaporated molten metal. As shown in Figure 4-A, the surfaces of the irradiated spots were rather smooth, with crater-like defects caused by the scattering of the evaporated molten metal, because of the increase of supplied energy.

Figures 4-B and 5-B show the results of penetration under the normal pulse condition of experiment B. The width and depth of penetration increased with increasing of the pulse width, because of the increase of supplied energy. As shown in Figure 4-B, the sectioned surface became rough and contained internal porosity with increasing pulse on time.

Figures 4-C and 5-C show the results of penetration under the modulated pulse condition of experiment C. Additional pulse with height (182A) of 66% of the original height was applied for 1, 2, and 4 ms after the original pulse (275A and 4ms). The width and depth of the penetration under the pulse modulation were equivalent to those under the normal pulse condition. As shown in Figure 4-C, the structure of the penetrated spots was smooth and contained less internal porosity under the additional pulse modulation. However, there remained a slight depression on the center of the irradiated spot at the additional pulse width of 4ms.

Discussion

Since pure titanium has low thermal conductivity and can utilize irradiated energy efficiently, titanium can be welded with less energy than precious metal alloys. However, when the energy becomes too high, evaporation of the metal from the irradiated surface deteriorates the quality of welding. Normal pulse irradiation produces deeper penetration with greater irradiation energy, but it also increases welding defects, such as porosity and rough surface. Therefore, suitable energy selection is necessary.

We remodeled the oscillating battery to control the welding energy using PWM, where additional pulse with a lower pulse height was applied after the initial pulse, to increase welding properties. We shot the single pulse to pure titanium, to observe the melting properties. We found internal porosity and rough surface on the specimens, since the cooling rate was too fast, and molten pool solidified before the wave focused.

We also found the room for the available energy to
obtain good welding was restricted. On the contrary, we could reduce internal porosity and surface roughness with PWM, since the solidification started after the wave of molten pool focused.

In addition, freedom of the available energy level increased with PWM, and we expected to apply PWM to numerically controlled welding, although we found a higher amount of evaporation and deeper concavity of molten pool.

We emphasize the selection of the optimized irradiating condition is essential to satisfy both the depth of penetration and quality of welding. We suggest the irradiation with a high-power pulse, for only a brief period, followed by irradiation with low energy for a
longer period, is practical in dental use.

Conclusion

In this study, we attached an experimental PWM circuit onto a commercial Nd: YAG laser welding machine, to evaluate the quality of penetration into the titanium plates. Normal pulse irradiation produced deep penetration, with welding defects, such as porosity and rough surface. On the other hand, irradiating with PWM produced a sound metal structure. Selection of the optimal irradiating condition was essential to satisfy both the depth of penetration...
and quality of welding. We suggest that two-stage irradiation with a high-power pulse for a brief period, followed by irradiation with low energy, for a longer period, is practical in dental use.

References


