Influence of irradiation conditions on the deformation of pure titanium frames in laser welding

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Due to its ease of use in connecting metal frames, laser welding is now applied in dentistry. However, to achieve precise laser welding, several problems remain to be resolved. One such problem is the influence of irradiation conditions on the deformation of titanium frameworks during laser welding, which this study sought to investigate. Board-shaped pure titanium specimens were prepared with two different joint types. Two specimens were abutted against each other to form a welding block with gypsum. For welding, three different laser waveforms were used. Deformation of the specimen caused by laser welding was measured as a rise from the gypsum surface at the opposite, free end of the specimen. It was observed that specimens with a beveled edge registered a smaller deformation than specimens with a square edge. In addition, a double laser pulse waveform — whereby a supplementary laser pulse was delivered immediately after the main pulse — resulted in a smaller deformation than with a single laser pulse waveform.

Key words: Laser welding, Titanium, Deformation

INTRODUCTION
In dentistry nowadays, laser welding is being increasingly used as a substitute metal connecting method because of a host of advantages it wields over conventional metal soldering. Laser welding is easy to perform because it can be done directly on the working cast. Laser welding also offers excellent corrosion resistance and mechanical strength because this technique does not use another type of metal in the joints of metal frameworks as in the case of soldering. In addition, since laser energy can be concentrated in a very small area, there are fewer effects of heating on the area surrounding the spot to be welded. This means that it is possible to repair a metal plate denture without removing the acrylic resin base or artificial teeth.

However, laser welding is not without flaws and it poses a few problems. During laser welding, it is easy to generate welding defects such as cracks and increased porosity at the joints of metal frameworks. These welding defects decrease the strength and durability of the connecting area of metal frameworks. It should also be highlighted that a metal framework can subtly deform due to the shrinkage that occurs when the laser pulse melts it momentarily. To achieve precise laser welding, it is therefore necessary to overcome these problems.

In our bid to resolve the problems posed by laser welding, this study set out to investigate the influence of irradiating laser waveforms and welded joint types on the deformation of metal frameworks using commercially pure titanium.

MATERIALS AND METHODS
Titanium specimens with square edge and beveled edge
JIS type II pure titanium (Titan 100, Shofu) was used as the experimental metal. To fabricate the specimens for laser welding, board-shaped wax patterns of $15 \times 10 \times 3$ mm dimensions were prepared. To investigate the influence of joint type on deformation, two types of patterns were hence prepared (Fig. 1). One pattern entailed a square-edge end, whereas the other was beveled by cutting diagonally at an angle of 45° from the top and bottom surfaces of the pattern. Joint thickness for the pattern with the beveled edge was 1 mm.

The patterns were invested using an alumina and magnesia-based investment (Titavest CB, Morita) and then cast using a centrifugal pressure and suction-type casting machine (Vulcan-T, Shofu). To ensure accurate joint contacts, the castings were adjusted using abrasive paper #400 and that the joint surfaces underwent alumina sandblasting for 10 seconds.

Abutted specimens in gypsum block
The joints of the two specimens for welding were abutted against each other on a flat surface and temporarily fixed with wax, and then the entire structure was placed on hard-type gypsum. As shown in Fig. 2, only one end of a specimen was

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embedded in gypsum. The other specimen was wholly exposed and temporarily fixed with sticky wax to prevent it from becoming detached from the gypsum surface. It should also be mentioned that the gypsum beneath the joint was removed, hence providing a small space.

**Laser apparatus and waveforms**

A laser welding apparatus (ML-2150A, Miyachi-technos.) was used. This machine used an Nd:YAG laser and allowed waveform regulation. For this study, the laser irradiation conditions were set at a peak power of 2.5 kW using a spot diameter of 0.6 mm, based on the results of a pilot study. On laser waveform, the following three types of waveforms were used:

- Waveform 1: only a main wave of 2.5 kW for 3.0 ms.
- Waveform 2: an additional second pulse of 1.6 kW for 2.0 ms immediately after the main wave.
- Waveform 3: an additional second pulse of 1.6 kW for 4.0 ms immediately after the main wave.

Five welding blocks with gypsum were prepared for each welding condition.

**Laser irradiation and measurement**

Laser irradiation was performed three times on the upper side of the specimen, first at the center of the joint between the abutted specimens in the welding block, and then at 1 mm each from both edges of the joint (Fig. 3).

Deformation of the specimen caused by laser welding was measured as a rise from the gypsum surface at the opposite, free end of the specimen (Fig. 4). The extent of rise at the end of the specimen was measured using a stereomicroscope (Scopeman, Moritex) at three points for each specimen and then the values were averaged.

**Statistical analysis**

Statistical analysis was performed using two-way ANOVA and Tukey’s multiple comparison test with a significance of $\alpha = 0.01$.

Some specimens were cut perpendicular to the joint after measurement. The cross-section was polished using abrasive paper #1000, and the effect of melting was examined using a stereomicroscope.
Table 1  Results of two-way ANOVA and Tukey’s multiple comparison test

<table>
<thead>
<tr>
<th>Factor</th>
<th>s.s.</th>
<th>d.f.</th>
<th>m.s.</th>
<th>Fo</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Joint type</td>
<td>1540.833</td>
<td>1</td>
<td>1540.833</td>
<td>22.363**</td>
</tr>
<tr>
<td>B: Laser waveform</td>
<td>1174.467</td>
<td>2</td>
<td>587.233</td>
<td>8.523**</td>
</tr>
<tr>
<td>A×B</td>
<td>138.067</td>
<td>2</td>
<td>69.033</td>
<td>1.002</td>
</tr>
<tr>
<td>E</td>
<td>1653.600</td>
<td>24</td>
<td>68.900</td>
<td></td>
</tr>
</tbody>
</table>

No interaction between A and B.
**: significant difference at p<0.01; ns: no significant difference
Square edge vs. beveled edge: **
Laser waveform 1 vs. laser waveform 2: **
Laser waveform 1 vs. laser waveform 3: **
Laser waveform 2 vs. laser waveform 3: ns

RESULTS

Fig. 5 shows the deformation values of the specimens due to laser welding. Maximum deformation occurred when the joint had a square edge and when laser waveform 1 was used. The average maximum deformation measurement was 109 μm. Conversely, minimum deformation (79 μm) occurred with a beveled edge and when laser waveform 2 was used.

When comparing between the two joint types, specimen deformation was generally smaller when a beveled edge was used. When comparing among the three laser waveforms, specimen deformation was seen to be smaller with laser waveforms 2 and 3, whereby a supplementary laser pulse was delivered immediately after the main pulse. Table 1 shows the results of two-way ANOVA and Tukey’s multiple comparison test. Significant deformation was observed with respect to both joint form and laser waveform, but there was no significant difference between laser waveforms 2 and 3.

Figures 6 and 7 show the cross-sectional images of the two joint types after irradiation with laser waveform 1. With the square-edged specimen (Fig. 6), depth of the keyhole caused by laser irradiation ranged only 1/2 to 2/3 of the specimen thickness. In contrast, with the beveled-edge specimen (Fig. 7), the
When using a laser welding apparatus for dentistry, the melting depth differs with the type of metal in use and irradiation conditions. Nonetheless, the depth generally does not exceed 2.0 mm. During laser welding, only the metal on the side of the joint that receives the laser pulse melts and then solidifies. Therefore, for optimal results, the thickness of the metal frame joint must be less than 2 mm. When the melted metal solidifies, only the laser-irradiated side of the metal frame is pulled at the joint, which then leads to a three-dimensional deformation of the structure. However, if the joint is sufficiently thin, the metal frame is expected to melt to the bottom of the joint with one laser pulse, which should then reduce the vertical deformation.

To examine the influence of different types of joints on the deformation of metal frames, board-shaped specimens of different joint thicknesses were thus prepared in this study. One joint had a square edge and its thickness was limited to 3 mm. The other joint had a beveled edge, which was produced by cutting diagonally from the top and bottom surfaces at one end, resulting in a joint thickness of only 1 mm.

With the square-edged specimen which had a joint thickness of 3 mm, the joint could not be melted to the bottom with one laser pulse as shown in Fig. 6. Therefore, shrinkage due to solidification occurred only at the melted upper surface of the joint, which could be the reason for the relatively large rise from the gypsum surface at the free end of the specimen. On the other hand, the thickness of the joint in the beveled-edge specimen was only 1 mm. As a result, the joint could be melted all the way through with one laser pulse as shown in Fig. 7. It is therefore conceivable that shrinkage deformation caused by solidification mainly occurred horizontally and did not affect the vertical rise of the specimen from the gypsum surface.

In the same connection regarding differences in deformation amount caused by irradiation conditions, the influence of different laser pulse waveforms was also investigated in this study. Laser waveform 1 was a single main pulse, while laser waveforms 2 and 3 had a supplementary pulse immediately after the main pulse. With the single laser pulse of laser waveform 1, solidification of the melted metal occurred rapidly, leaving behind residual stress in the joint. Consequently, the rise from the gypsum surface at the opposite end of the specimen—which was caused by shrinkage at the joint—was quite large. On the other hand, the second pulse applied in laser waveforms 2 and 3 decreased the rate of metal solidification, thereby somewhat suppressing the deformation of specimens.

In a study by Lee [13], it was reported that when the supplementary pulse was short, residual stress

**DISCUSSION**

Laser welding is an alternative method of connecting metal frames. It relies on the conversion of light energy into thermal energy when laser is applied to a metal surface. Research on the use of laser welding in dentistry began in the early 1970s [7-10] chiefly because of its ease of use: laser welding can be performed directly on the working cast. However, the metal framework is easily subjected to subtle deformation due to shrinkage of the metal when melted by laser irradiation in the connecting area. To alleviate this adverse effect, various laser welding methods have been attempted [11,12].

In laser welding, metals with high light absorbability and low thermal conductivity are easy to weld because of efficient conversion of light energy to thermal energy at the metal surface. On this premise, titanium is superior to platinum, gold, or silver. For the same reason, JIS type II pure titanium was selected and used in this study.
developed and shrinkage occurred. On the other hand, when the supplementary pulse was long, the amount of melted metal increased and so did shrinkage. However, in this study, no significant differences in specimen deformation between laser waveforms 2 and 3 were observed. In light of the contradictory findings, more detailed experiments are required to examine the influences of laser output and the duration of second laser pulse on shrinkage due to metal solidification during laser welding.

CONCLUSIONS

Having examining the influences of joint type and laser waveform on the deformation of pure titanium frameworks during laser welding, the following results were obtained:

(1) When comparing the joint types, specimens with a beveled edge yielded less deformation than specimens with a square edge.

(2) When comparing the laser waveforms used, the deformation caused by laser waveforms 2 and 3, whereby a supplementary pulse was applied immediately after the main pulse, was less than that using laser waveform 1 which entailed only a single laser pulse.

(3) Within the experimental conditions employed in this study, no significant differences in metal framework deformation were observed between laser waveform 2 (which had a supplementary pulse duration of 2 ms) and laser waveform 3 (which had a supplementary pulse duration of 4 ms).

REFERENCES


