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# Effect of laser irradiation conditions on the laser welding strength of cobalt-chromium and gold alloys

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(Received 5 February and accepted 2 June 2011)

**Abstract:** Using tensile tests, this study investigated differences in the welding strength of casts of cobalt-chromium and gold alloys resulting from changes in the voltage and pulse duration in order to clarify the optimum conditions of laser irradiation for achieving favorable welding strength. Laser irradiation was performed at voltages of 150 V and 170 V with pulse durations of 4, 8, and 12 ms. For cobalt-chromium and gold alloys, it was found that a good welding strength could be achieved using a voltage of 170 V, a pulse duration of 8 ms, and a spot diameter of 0.5 mm. However, when the power density was set higher than this, defects tended to occur, suggesting the need for care when establishing welding conditions. (J Oral Sci 53, 301-305, 2011)

**Keywords:** laser welding; cobalt-chromium alloy; gold alloy; welding condition; welding strength.

## Introduction

Dental laser welding was first reported by Gordon et al. (1) in 1970, in which bridges and attachments were joined using the Nd:YAG laser. Thereafter, dental laser welding machines have been applied clinically (2,3). Laser welding is advantageous because it can concentrate laser energy on minute areas of metal and is applicable

to areas near resin, which is susceptible to heat. Since it melts base alloys themselves, a higher welding strength can be achieved, in comparison with soldering. Furthermore, no investment is required to fix the metals being irradiated.

However, as laser welding began to be applied to the dental field relatively recently, a number of points remain to be clarified, such as the optimal welding conditions for different types of metal.

Previous studies have investigated the mechanical properties (4-13), penetration depth (14-16), and metal microstructure (4,11,13) after laser welding. However, as the welding strengths of alloys vary according to the combination of metals within them, the welding conditions for different types of metal have not been fully clarified. In the present study using tensile tests, we investigated the welding strength of casts of cobalt-chromium and gold alloys after laser welding at different voltages and pulse durations to clarify the optimum laser irradiation conditions for achieving favorable welding strength.

## Materials and Methods

Cobalt-chromium alloy (Biosil L, Dentsply-Sankin, Tokyo, Japan; composition as mass%: Co 62.5, Cr 30.5, Mo 5.0, Si 1.0, Mn 0.4, C 0.3, N 0.3) and Type IV gold alloy (PGA-13, Ishifuku Metal Industry Co., Ltd., Tokyo, Japan; composition as mass%: Au 70.0, Pt 3.0, Ag 4.7, Pd 2.0, Cu 20.0, others 0.3) were used. Phosphate-bonded investment (Snow White, Shofu Inc., Kyoto, Japan) for high-temperature casting was used for cobalt-chromium alloy, and gypsum bonded investment (Cristobalite Investment, GC Corp., Tokyo, Japan) was employed to

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cast the gold alloy.

### Specimens

To produce specimens for laser welding,  $\phi 1.2 \times 30$  mm vinyl line wax (R1.2, Hayashi Dental Co., Kanagawa, Japan) was used as the wax pattern. The wax pattern was invested in a  $\phi 40 \times 55$  mm casting ring, and each investment was mixed using a vacuum mixer (Vacuum Mixer VM-112T, J. Morita Corp., Kyoto, Japan). High-frequency casting (Argon caster-C, Shofu Inc.) was performed, followed by sand-blast treatment of the cobalt-chromium alloy cast using alumina (High Alumina, Shofu Inc.; average particle size  $53 \mu\text{m}$ ) and a sand-blaster (HiBlaster Ovaljet, Shofu Inc.; air pressure 0.4 MPa). The centerline average roughness of the sand-blasted surface was  $1.3 \mu\text{m}$ . The oxide film on the casting of the gold alloy was removed using an acid-treatment agent (Gold / Para-cleaner, Ishifuku Metal Industry Co., Ltd.) and an ultrasonic cleaning device (Sweep Zone S140, Sybron Dental Specialties Japan Inc., Tokyo, Japan) for 5 minutes. Thereafter, both cast alloys were sufficiently washed using the ultrasonic cleaning device, and then cut vertical to the long axis to produce specimens 15 mm in length using a precision cutting machine (MC-501, Maruto Instrument Co., Tokyo, Japan) and resinoid blades (# 320, Maruto Instrument Co.). The specimens were cleaned ultrasonically after being cut.

### Laser welding

A Nd:YAG laser (Neolaser P, Selec Co., Osaka, Japan) was used for laser welding, and no filler metal was employed. Laser irradiation was performed at voltages of 150 and 170 V and pulse durations of 4, 8, and 12 ms at 16 sites around the specimens, setting the pulse frequency to 1 Hz, and spot diameter to 0.5 mm. The overlap area was approximately 53%. Furthermore, the laser energy under each irradiation condition was measured using a thermopile sensor (30A-N-SH, Ophir Optonics Inc., Jerusalem, Israel).

Laser irradiation sites were set in areas of abutment between cobalt-chromium and gold alloys, and irradiation was performed after fixing the specimens in a jig.

### Tensile testing

For tensile tests, the welding strength was measured at a cross-head speed of 1.0 mm/min using a universal testing machine (Type 5567, Instron Corp., Canton, MA, USA). Seven specimens were tested under each irradiation condition. Two-way layout analysis of variance and Tukey's multiple comparison test of the welding strength were performed.

### SEM observation of the fracture surface

The fracture surface after the tensile test was observed using a field emission scanning electron microscope (S-4300, Hitachi High-Technology Corp., Tokyo, Japan) with an acceleration voltage of 15 kV at  $\times 50$  magnification.

## Results

### Irradiation energy

The results of measurement of laser energy under each irradiation condition are shown in Fig. 1. When the voltage was 150 V and pulse duration was 4, 8, and 12 ms, the laser energy was 0.98, 2.08, and 3.19 J, respectively. The corresponding energy levels at 170 V were 1.76, 3.77, and 5.72 J, respectively.

### Welding strength

The results of tensile tests, in which welding was performed under differing laser irradiation conditions, are shown in Fig. 2. When the voltage was 150 V, the tensile strength was lower than 320 MPa, showing low values for every pulse duration. However, when the voltage was 170 V, the tensile strength exceeded 500 MPa, showing high values for every pulse duration. The maximum tensile strength, achieved when the pulse duration was 8 ms, was 698 MPa. The results of statistical tests are shown in Fig. 2. A significant difference in tensile strength was noted between 150 V and 170 V. Furthermore, when the voltage was 170 V, there was a significant difference in tensile strength between a pulse duration of 4 ms and one of 8 ms. Two-way analysis of variance demonstrated no interaction between voltage and pulse duration.

### Observation of the fracture surface

Figure 3 shows examples of SEM photographs of the fracture surface after welding under each laser irradiation condition. When the voltage was 150 V and pulse duration 4 ms, the penetration depth of the molten area was approximately 0.1-0.2 mm, and the inner area was completely unmelted. When the voltage was 150 V and pulse duration 8 ms, the penetration depth was approximately 0.2-0.3 mm. When the voltage was 150 V and pulse duration 12 ms, the central area of approximately 0.4-0.6 mm was unmelted. On the other hand, when the voltage was 170 V and pulse duration 4 ms, unmelted regions were detected in the central area, and furthermore, large pores appeared to be formed due to imperfect back-filling of the keyhole. When the voltage was 170 V and pulse duration 8 ms, a large number of dimples were observed, and ductile fracture was evident. When the voltage was 170 V and pulse duration 12 ms, although

the specimens were melted up to the central area, pores were present in the area of ductile fracture.

## Discussion

When performing laser welding, it is necessary to set appropriate laser irradiation conditions (14,16), including voltage, pulse duration, and spot diameter, depending on the type, morphology, and surface condition of the alloys that need to be joined, in order to achieve a sufficient melting penetration depth, without welding defects. Generally, the molten penetration depth increases with voltage (14,16). Furthermore, when the spot diameter is

reduced, the power density becomes high, and the molten penetration depth is considered to increase (14,16). In laser welding, laser energy is absorbed by the metal surface, and the optical energy of the laser is transformed to thermal energy, which melts and joins the target metals. Under conditions of low optical energy, only the surface layer is heated, and a thermal conductive-type molten pool morphology with a lower aspect ratio (proportion of the penetration depth into molten metal relative to diameter) develops. On the other hand, when the optical energy is high, a keyhole-type molten pool morphology develops in which the penetration depth of the molten

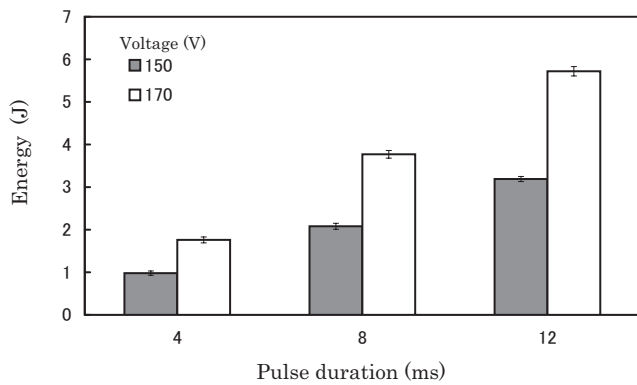


Fig. 1 Laser energy under each irradiation condition.

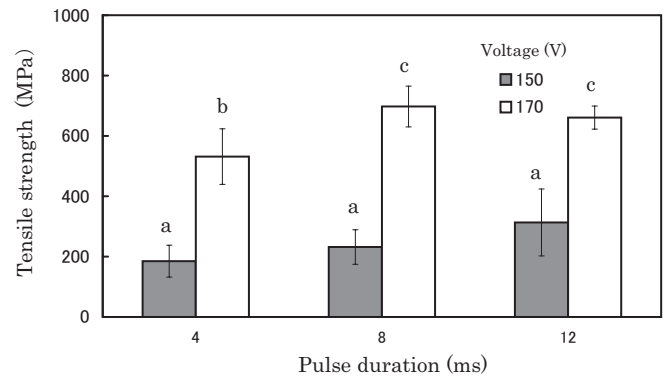


Fig. 2 Tensile strength of the specimens under each irradiation condition. Different letters indicate statistically significant differences ( $P < 0.05$ ). The error bar shows SD ( $n = 7$ ).

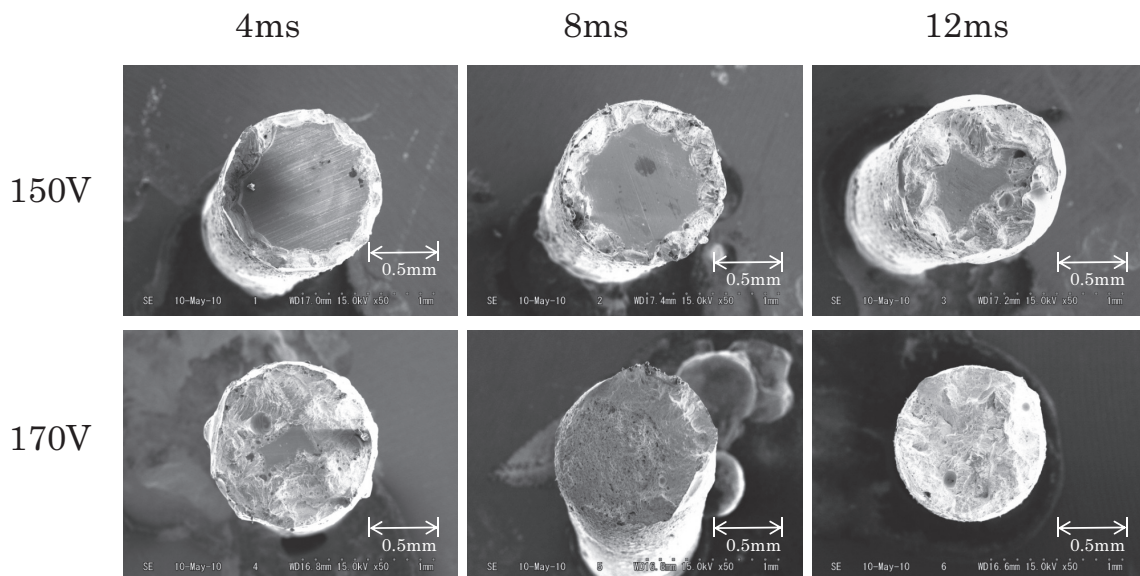


Fig. 3 SEM photographs of the fracture surface after welding under each laser irradiation condition.

metal exceeds its diameter. However, when excessive optical energy is applied, sputtering of the molten metal occurs (17), leading to the formation of multiple pores and causing a welding defect. Therefore, laser welding requires appropriate irradiation conditions to be set, so that no welding defect develops.

In the present study, to investigate the optimum laser irradiation conditions for welding cobalt-chromium and gold alloys, laser welding was performed setting the voltage to 150 V or 170 V and the pulse duration to 4, 8, or 12 ms. The pulse frequency was set at 1 Hz, and the spot diameter at 0.5 mm.

We found that a maximum tensile strength of 698 MPa was achieved when the voltage was 170 V and the pulse duration 8 ms. Furthermore, when the voltage was 170 V and the pulse duration 12 ms, the tensile strength was 661 MPa, which was sufficiently high, and did not differ significantly from that achieved with a pulse duration of 8 ms. The tensile strength of cobalt-chromium alloy is 870 MPa (18), whereas that of gold alloy is slightly lower at 776 MPa (18). The tensile strength achieved in this study after welding cobalt-chromium and gold alloys was about 700 MPa, which approximates that of gold alloy, and is considered to be a sufficient welding strength.

On the other hand, when the voltage was 170 V and the pulse duration 4 ms, the tensile strength was 513 MPa, which was significantly lower than that at a voltage of 170 V and a pulse duration of 8 ms. When the voltage was 150 V and the pulse duration 4 ms, the tensile strength was 185 MPa, which was the lowest value recorded. For the same pulse duration, the tensile strength was significantly higher at 170 V than at 150 V.

The energy in Fig. 1 divided by the spot diameter equals the energy density. The energy density divided by the pulse duration equals the power density. Figure 4 shows the calculated power density. From this figure, it

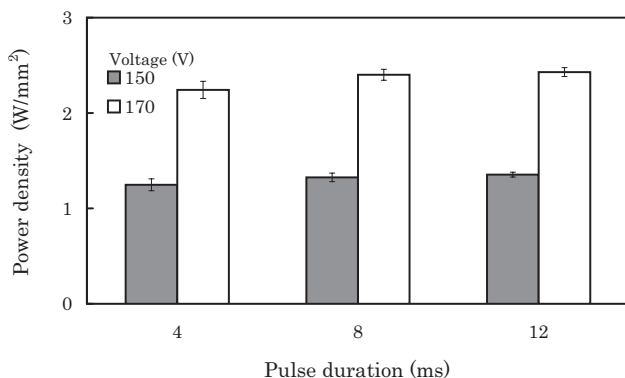


Fig. 4 Power density under each irradiation condition.

can be seen that when the voltage was 150 V, the power density was 1.25-1.35 W/mm<sup>2</sup> for any pulse duration. When welding conditions were evaluated using SEM photographs of the fracture surface, it was suggested that the casting was not completely melted up to the central area at a low voltage of 150 V, and the molten penetration depth was less than 0.6 mm. Therefore, it was considered that, at a low power density voltage of 150 V, the molten morphology was of the thermal conductive type, with a shallow molten penetration depth, which led to a low tensile strength.

On the other hand, at a voltage of 170 V, the power density was 2.2-2.4 W/mm<sup>2</sup> for any pulse duration, showing a deep molten penetration depth. These findings suggest that laser welding requires a sufficient power density to melt metals.

As Baba et al. (16) have reported, the molten penetration depth differs depending on the type of alloy and irradiation conditions employed. Differences in the laser absorption rate, thermal conductivity, and density of alloy elements influence the molten penetration depth. In the case of gold, for example, the optical absorption rate is 3%, thermal conductivity is 2.97 W/cm·K, and density is 19.3, whereas for copper the corresponding values are 32%, 0.71 W/cm·K, and 8.9, respectively. When a laser is used to irradiate metals, they absorb some of the light and reflect the remainder. For metals with a low thermal conductivity, optical energy changes to thermal energy, leading to development of high temperature in some areas. Furthermore, the surface temperature tends to increase when the density and specific heat of metals are low. Therefore, the molten penetration depth becomes deeper for cobalt-chromium alloy than for gold.

The molten penetration depth is also influenced by the surface conditions of metals, such as differences in the optical absorption rate between the surface of cast bodies and a mirror-polished surface. It is also influenced by metal organization and the presence of an oxide film on the mirror surface of the metal. Therefore, not only laser irradiation conditions, but also various other properties such as the metal surface and atmosphere, are considered to influence the results of laser welding.

In laser welding, it is necessary to avoid the development of fragile compounds at the join interface during the process of metal melting and cooling. From the binary alloy phase diagram for cobalt and gold (19), although the alloy in the join area is eutectic, a high welding strength is thought to be achieved, since cobalt and gold are a good weldable combination.

However, if the power density is set higher than that used in this study, defects tend to occur, and therefore



care is needed to establish suitable welding conditions.

Although most commercially available dental laser welding machines use a Nd:YAG laser, they have different specifications, such as the laser output and light condensers employed. Therefore, the laser irradiation conditions established in this study should be regarded as a standard, and may not always be applicable for every welding system.

Casts of cobalt-chromium alloy and gold alloy 1.2 mm in diameter were welded by laser irradiation using voltages of 150 V and 170 V and pulse durations of 4, 8, and 12 ms to clarify the optimum conditions for obtaining a high welding strength, and the following results were obtained.

1. The tensile strength was significantly higher at 170 V than at 150 V.
2. At 150 V, it was impossible for the laser to cause melting up to the central area of the casting.
3. The maximum tensile strength was achieved at 170 V and a pulse duration of 8 ms. Under these conditions, the tensile strength was 698 MPa.
4. The fracture surface under the above conditions showed ductile fracture.

These results show that for the welding of cobalt-chromium and gold alloys, a good welding strength can be achieved when the applied voltage is 170 V, the pulse duration is 8 ms, and the spot diameter is 0.5 mm.

### Acknowledgments

This study was supported in part by the Sato Fund (2008) of Nihon University School of Dentistry.

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