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Effect of Nd:YAG Laser Parameters on the Penetration Depth of a Representative Ni–Cr Dental Casting Alloy

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Abstract

The effects of voltage and laser beam (spot) diameter on the penetration depth during laser beam welding in a representative nickel–chromium (Ni–Cr) dental alloy were the subject of this study. The cast alloy specimens were butted against each other and laser welded at their interface using various voltages (160–390 V) and spot diameters (0.2–1.8 mm) and a constant pulse duration of 10 ms. After welding, the laser beam penetration depths in the alloy were measured. The results were plotted and were statistically analyzed with a two-way ANOVA, employing voltage and spot diameter as the discriminating variables and using Holm–Sidak post hoc method ($\alpha = 0.05$). The maximum penetration depth was 4.7 mm. The penetration depth increased as the spot diameter decreased at a fixed voltage and increased as the voltage increased at a fixed spot diameter. Varying the parameters of voltage and laser spot diameter significantly affected the depth of penetration of the dental cast Ni–Cr alloy. The penetration depth of laser-welded Ni–Cr dental alloys can be accurately adjusted based on the aforementioned results, leading to successfully joined/repaired dental restorations, saving manufacturing time, reducing final cost, and enhancing the longevity of dental prostheses.

Introduction

Laser beam welding (or laser welding) has been introduced to dental technology during recent decades as an alternative method to soldering, brazing, or tungsten inert gas (TIG) welding [1–4]. In laser welding, only a very narrow zone is affected by heat [5], thereby diminishing distortion [6, 7] and making it possible to join very thin parts [8], such as the parts of metallic dental restorations. In some cases, a filler metal is not required, which simplifies the procedure, and the joining of different alloys is feasible. Laser welding generally offers higher corrosion resistance of the joints sustainability and, in a few cases, the enhancement of selected mechanical properties and the protection of adjacent esthetic materials (i.e., dental resin) that have lower melting points. The safety, speed, and simplicity of this welding procedure are just a few more advantages over conventional welding techniques, such as brazing and TIG welding. However, the complexity of selecting the laser beam parameters, the relatively limited penetration depth of the laser beam and the requirement for additional training of the dental technician should be considered among the limitations of this method [9, 10].

Successful laser welding depends on the proper adjustment of many parameters. These parameters can be divided into four general categories: parameters associated with the laser beam, the focusing lens, the shielding gas, and the materials to be welded (Fig. 1). After the material and the shielding gas parameters have been determined, only the laser beam parameters remain for the user to adjust; the focusing lens parameters are predetermined by the laser device. The laser beam parameters have a direct effect on the penetration depth of the beam, which affects both the mechanical and corrosion properties of the weld [1, 4, 10–13]. Adjusting these parameters could result in either high- or low-quality joints, as shown schematically in Fig. 2. Thus, knowledge of the relationship between the laser beam parameters and the resultant penetration depth of the beam for a given dental alloy is of great importance when laser-welding dental metallic restorations.

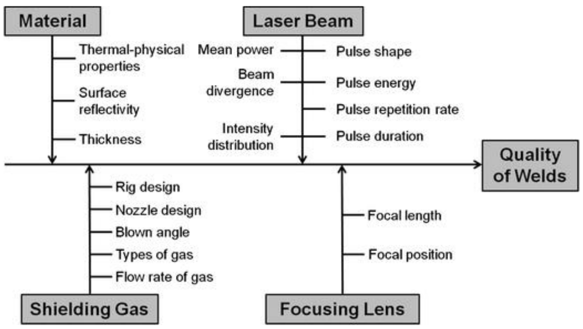

Fig. 1 A schematic illustration of factors affecting the quality of laser welding joints (redrawn with modifications from Tzeng [37])

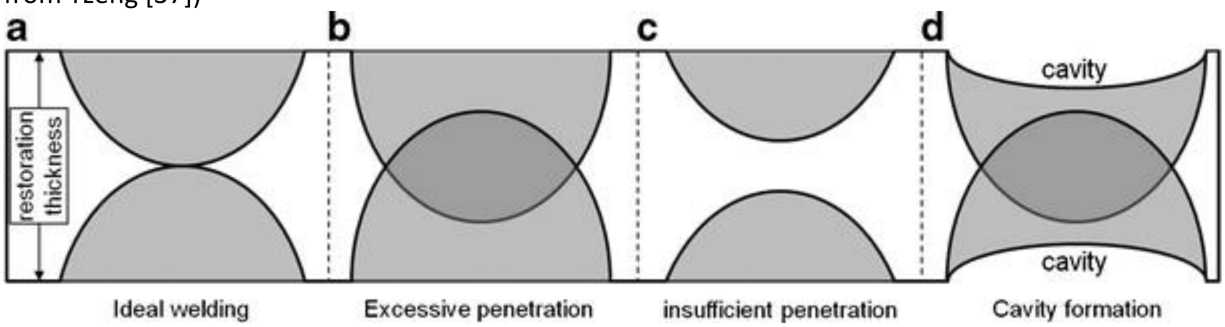

Fig. 2 The proposed penetration depth (*a*) combined with 80 % [37] spot overlapping (not shown in the figure) for ideal welding/repairing of metallic dental restorations. Common morphologies of non-ideal laser welding attributed to inappropriate adjustments of laser parameters are excessive penetration (*b*), insufficient penetration (*c*), and undesirable cavity formation (*d*)

Many studies that involve the use of laser welding on dental alloys have been published on commercially pure (CP) Ti [2–4, 8, 10, 11, 14–23], Ti-based alloys [3–5, 9–11, 22, 24–28], noble metal alloys [1, 10–12, 28–32], and nonprecious metal alloys [2, 4, 6, 10, 11, 13, 21, 22, 29, 33–36], but few studies have focused on the effect of laser welding on the penetration depth [1, 4, 7, 8, 10–12, 18]. Furthermore, a very limited number of publications exist that describe the overall effect of laser welding on nickel–chromium (Ni–Cr) alloys [2, 13, 33], and none of these publications provide a wide range of information about the relationship between the laser beam penetration depth and the laser parameters.

The purpose of this study is to correlate the laser beam parameters with the penetration depth for a representative Ni–Cr-based dental alloy. The null hypothesis was that the penetration depth for Ni–Cr dental alloy during laser welding was not dependent on voltage and spot size of laser beam.

Materials and methods

The material used in this study was a Ni–Cr alloy (System KN, Adentatec GmbH, Koln, Germany) with a nominal composition of 62.3 % Ni, 25 % Cr, 11 % Mo, 1.5 % Si, <0.1 % Mn, and <0.1 % others (weight percent). To prepare the specimens, 168 hexagonal wax patterns were prepared by employing a hexagonal matrix (6 mm in width for each side and 10 mm in length). The wax patterns were invested with a phosphate-bonded investment (GC Stellavest, GC Europe NV, Belgium). Casting was performed using a centrifugal casting machine (Ducatron S3, Ugin'Dentaire, Seyssins, France), according to the alloy manufacturer's instructions. Before casting, the molds were preheated at 910 °C, and after casting, they were left on the bench to cool to room temperature. The cast blocks were then divested and ground with 600 grit SiC paper to remove flashes and maintain a flat surface. The hexagonal surfaces were sandblasted with 110 µm alumina oxide particles to reduce laser beam reflection during welding, and the specimens were ultrasonically cleaned with acetone for 5 min.

Two specimens were fixed in a jig with one of their six surfaces (10 mm × 6 mm) butted against each other, leaving no gap. Spot welding was performed parallel to that interface (along the 6 mm side), employing a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser apparatus (ALDT30, Alpha Laser, Puchheim, Germany). The laser source was a Nd:YAG laser emitting pulses with 1.064 nm wavelength with a maximum pulse energy of 42 J and a maximum power of 45 W. Two laser pulses were applied, one after another, to each side without overlapping, and these pulses were equidistant between the spots and the edges of the specimen. After welding, the two parts were separated with the use of pliers and rotated by 60° to weld the next pair of spots. This procedure was repeated for all sides of the specimen, providing 12 spots for a single welding condition. To obtain a wide range of results, the laser parameters used were voltages of 160–390 V in increments of 30 V and spot diameters of 0.2–1.8 mm in increments of 0.2 mm, providing 81 different combinations with power density ranging from 0.54 W/mm^2 up to 37.75 W/mm^2. The pulse duration was set to 10 ms. The laser welding was performed under atmospheric conditions (without a shielding gas), and the distance between the laser and the welding surface was set at the focal point of the laser beam.

Although the penetration depth of the laser beam does not necessarily match the melting depth, the term "penetration depth" has been extensively used in the literature to reflect the melting depth in laser welding. Therefore, it is used similarly in this study to describe the distance between the surface of the weld and the maximum melted depth of the alloy. A measuring microscope (Model STM, Olympus Optical Co. Ltd., Tokyo, Japan) was employed to measure the penetration depth of the laser beam. The penetration depth was measured on both sides of each of 12 pulses, and the results were averaged, and the standard deviation was calculated. A stereomicroscope (Leica M80, Leica Microsystems, Wetzlar, Germany) coupled with a digital color camera system (Leica DFC295, Leica Microsystems, Wetzlar, Germany) was also employed to observe the morphology of the welded cross sections.

Penetration depth was statistically analyzed with a two-way ANOVA at an $\alpha = 0.05$ significance level, employing the voltage and spot size as the discriminating variables. The Holm–Sidak post hoc procedure was then used to determine any significant differences among groups ($\alpha = 0.05$).

Results

Figure 3 shows the measured penetration depths for various laser beam spot diameters and voltages. Statistically significant differences demonstrated the direct effect of the spot diameter ($P < 0.001$) and the voltage ($P < 0.001$) on the measured penetration depth, and an interaction between the spot size and the voltage was also determined ($P < 0.001$). The penetration depth values varied from negligible to approximately 4.7 mm. Additionally, the penetration depth increased with a decreasing spot diameter at a fixed voltage value or with an increasing voltage at a fixed spot diameter value (Fig. 3). However, when the spot diameter value was decreased to less than 0.4 mm, the penetration depth values also decreased. Furthermore, a sharp increase in the penetration depth values was observed for spot diameter values between 1.0 and 0.8 mm at an applied voltage of 330 V or more, instead of the smoother increase that characterizes the rest of Fig. 3. A gradual significant increase was also observed at lower voltage values when the spot diameter was decreased from 1.0 to 0.4 mm; however, this increase was still smoother than that observed between 330 and 390 V. Voltages in the range of 160–210 V exhibited a less effect on the penetration depth for the whole range of spot diameters tested.

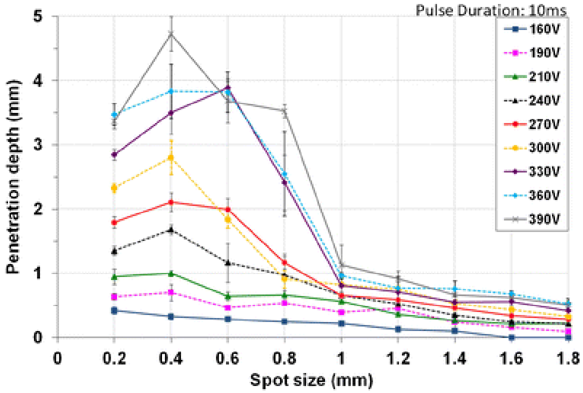

Fig. 3 The evolution of the laser beam penetration depth (in millimeters) versus the spot diameter (in millimeters) for various voltage values (in volts) and constant pulse duration (10 ms)

Stereomicroscope images of four different morphologies observed at the welded cross sections are shown in Fig. 4. The schematic diagram in Fig. 5 correlates each pair of spot diameter and voltage values to one of the four different morphologies (labeled as A, B, C, or D).

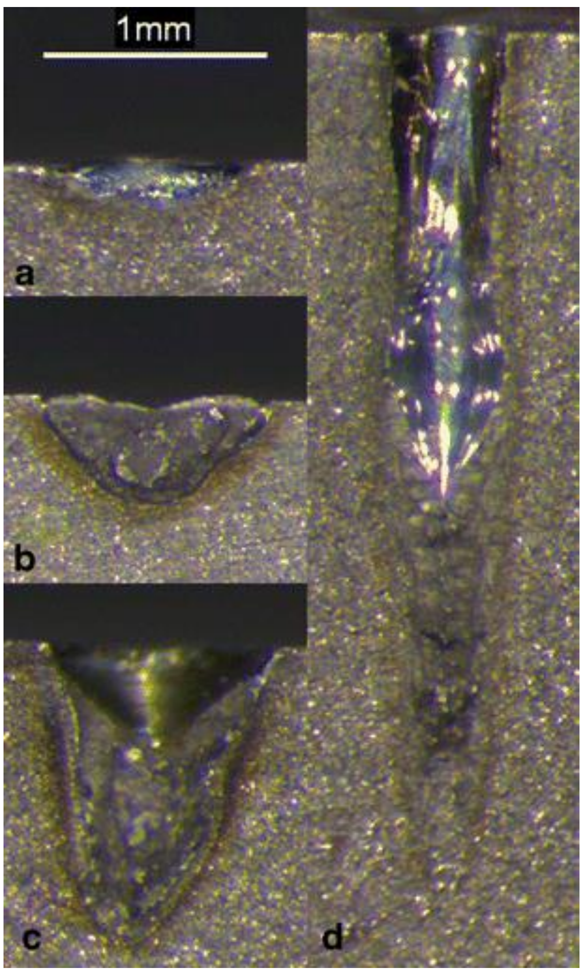

Fig. 4 Stereomicroscope images of the four possible weld morphologies (cross sections) observed after laser welding and detaching the two welded parts in the Ni–Cr dental alloy. *a* Negligible or shallow penetration depth. *b* Intermediate penetration depth. *c* Intermediate and higher penetration depth with cavity formation due to material vaporization. *d* Highest penetration depth with extensive material vaporization

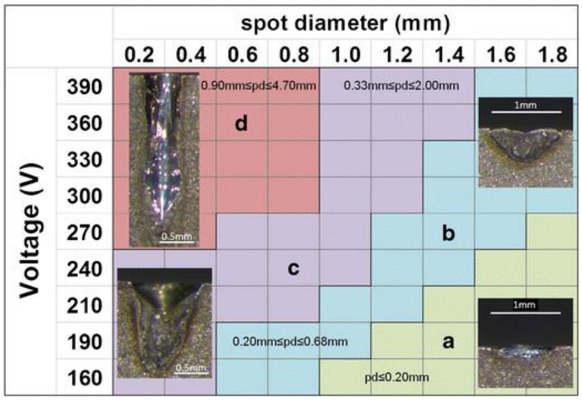

Fig. 5 A schematic diagram showing the cross sections of the four possible weld morphologies (labeled as A, B, C, or D) observed after laser welding a Ni–Cr dental alloy for various values of the spot diameter (in millimeters) and voltage (in volts). The minimum and maximum penetration depth measured in each area is also indicated (*pd* penetration depth)

Area “A” on the diagram in Fig. 5 represents penetration depths of up to approximately 0.20 mm deep and is described as “negligible or shallow penetration depth.” No pores or cracks were detected, and the surface could be characterized as rather smooth, without any evidence of cavities on the surface of the welds. Area “B” on the diagram represents penetration depths beginning at approximately 0.20 mm deep, which is described as “intermediate penetration depth.” This cross section also exhibited no cavities. The maximum penetration depth of this area was approximately 0.68 mm which is achievable at a spot diameter of 1.6 mm and a voltage of 360 V. The welds for which a massive vaporization of material took place are located in area “C.” These welds exhibit an “intermediate and higher penetration depth with cavity formation”; the maximum cavity depth was 0.50 mm. The maximum measured penetration depth in this area was approximately 2 mm and corresponds to a spot diameter of 0.60 mm and a voltage of 270 V, with a cavity depth of approximately 0.10 mm, whereas the minimum measured penetration depth was 0.33 mm (at a spot diameter of 0.40 mm and a voltage of 160 V). The welds for which the cavity was formed by massive vaporization of the material and exceeded 0.50 mm in depth are represented by area “D,” which represents the “highest penetration depth with deep cavities.” This area includes the highest penetration depth measured in this study, approximately 4.7 mm, which corresponds to a spot diameter of 0.4 mm and a voltage of 390 V. The same conditions also resulted in the deepest cavity depth caused by vaporization, which was measured at approximately 4.50 mm.

Discussion

Based on the findings of this study, the null hypothesis must be rejected as the laser parameters tested found to be significantly affecting the penetration depth of laser beam within the mass of the tested Ni–Cr dental alloy. The four different weld morphologies observed (Fig. 4) were caused by varying the laser parameters of voltage and spot diameter. The conditions for areas A and D (Fig. 5) resulted in negligible penetration and deep penetration with extensive material vaporization, respectively. This is attributed to the change in power dissipated per unit area or the laser beam power density (P_D) given by the following equation:

$$P_{\mathrm{D}} = 4E/t\pi d^2$$

(1)

where *E* is the pulse energy (in joules), *d* is the spot diameter (in millimeters), and *t* is the pulse duration (in milliseconds) [10, 37]. *E* is given by the following equation:

$$E = tP_{\mathrm{P}}$$

(2)

where P_P is the average peak power (in kilowatts) [37].

Generally, when the voltage is increased, the average peak power increases which, in turn, increases the pulse energy (Eq. 2). Thus, when the spot diameter and pulse duration are constant (d, t = constant in Eq. 1), the average peak power density increases, and the penetration depth increases. This explains why the increment of the penetration depth is proportional to the increment of voltage. Moreover, as Eq. 1 describes, a constant voltage corresponds to constant pulse energy, and a decrease in the spot diameter results in an increase in the power density. This explains the increase of penetration depth with the decrease in spot diameter (the pulse duration was kept constant in this study).

The increases in the penetration depths that were observed between the spot diameter values of 1.0 and 0.8 mm for voltage values of 330 V ($P = 0.003$), 360 V ($P = 0.003$), and 390 V ($P = 0.003$) may be attributed to the change in the welding modes and the keyhole effect, which Baba and Watanabe [10] suggested that this could occur in other dental alloys. Similar behaviors to that observed for the Ni–Cr alloy have also been reported in other dental alloys, in which an increase in the laser beam penetration depth was observed at critical values of the spot diameter [1, 8, 10]. As the parameters of voltage and spot diameter vary, the power density value also varies (Eq. 1). When power density exceeds a critical value, the vaporization of the locally molten metal creates a cavity, which promotes the further penetration of the beam. The same phenomenon also occurs for voltage values below 330 V and spot diameter values below 0.8 mm, which explains the shift in the slope to the left in Fig. 3. Furthermore, the keyhole effect does not seem to occur at any spot diameter for very low voltage values such as 160 V because the critical value for the laser power density for vaporization cannot be attained. This explains why an abrupt change in the slope was not observed on the diagram for the experimental conditions in this study.

Perret et al. [25] showed that the formation of a keyhole in a metallic target is a complex phenomenon affected by multiple factors [12, 25] and is not only a function of the voltage, the spot diameter, the pulse duration, or other laser parameter values. The pulse shape [12, 23] and other pulse characteristics [25] need to be taken into account. This means that further research is required to correlate the keyhole effect with the critical values for power density and various laser parameters for a given material. Thus, the formation of the keyhole depends not only on a specific critical value of power density, as Baba and Watanabe [10] suggest, but also on the variation of the spot diameter, as observed in the present study. In addition to the change in the weld mode and the large increase in the penetration depth, no further increase occurred below a spot diameter of 0.4 mm for most voltage values (Fig. 3), although the power density reaches its maximum value at a spot diameter of 0.2 mm, according to Eq. 1. This also leads to the conclusion that there must be an upper limit on the power density, above which no further penetration depth could be achieved.

According to Eq. 1, the power density exhibits its lower values within area A of Fig. 5. For the extreme conditions of a spot diameter of 1.8 mm and a voltage of 160 V, the power density value becomes the minimum possible for this study and is practically insufficient for penetration. Areas A and B in Fig. 5 include the safest conditions for laser welding a Ni–Cr alloy, resulting in a smooth surface. Welding within area C is also satisfactory, but the cavity that forms on the surface of the weld could reach up to 0.50 mm for the conditions that are closer to the border with area D. Finally, welding with the laser parameters set within area D is not recommended, as in many cases, the cavity formed was equal to the penetration depth, which is undesirable when welding prostheses.

Clinically, this information could be useful, depending on the user's experience in welding prostheses. Knowing the effect of the laser parameters on the penetration depth, the exact depth can be determined from Fig. 5 for any Ni–Cr prosthesis. Control of penetration depth along with attention to other factors such as the joint design

[21], the work piece shape, the number of pulses, the overlap of the pulses, or the preservation of mechanical properties, should guarantee quality welds.

Although shielding gas is necessary to prevent undesirable oxidization during laser welding of noble metal alloys and CP Ti or Ti-based alloys [11, 17], the use of shielding gas during the welding of nonprecious metal alloys is somewhat controversial, as previous studies have found the use of shielding gas to be either essential [13] or detrimental [11]. The absence of shielding gas in this study did not result in low-quality welds, as have been reported for laser welding of Ni–Cr or other nonprecious metal dental alloys [4, 22, 33], and the various penetration depth values achieved were close to those of other dental alloys [10]. Further research is required to clearly define the effect of the shielding gas parameter on Ni–Cr dental alloys during laser welding.

The quality of the welds of dental metallic restorations after laser welding is subject to the appropriate adjustment of the laser welding parameters. This study investigated the effect of the laser beam parameters on the penetration depth, but the effects of other factors, such as the use of shielding gas, the selection of appropriate seam geometry of the assembled two metallic parts remain unclear. Thus, this is an interesting area for further research.

Conclusions

The laser beam penetration depth of the laser welded Ni–Cr dental alloy was significantly affected by varying the voltage or spot diameter parameters, as the penetration depth increased with decreasing spot diameter and increasing voltage. The values of the parameters and the achieved penetration depth were used to categorize the cross section of the weld as one of four different morphologies, each of which should be considered when laser welding these alloys.

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