Proposals for Optimization of Laser Welding in Prosthetic Dentistry

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Keywords
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Abstract

This paper points out each key parameter involved in laser welding and discusses the parameters' effects on weld microstructure and defects detected inside the weld. Solutions are proposed to adjust the parameters to provide an optimal dental assembly. Metallurgical effects as well as defects are briefly discussed. A welding procedure adapted to different compositions of dental alloys is proposed.

Laser-welding technology has been successfully adopted in many industrial fields, including the electronic, military, aeronautic, and automobile industries, as well as in jewelry technology, in which high precision and quality of assembly are required. The first tests in dental laboratories were conducted in 1970 by Gordon and Smith,[1] who found laser welding appropriate due to its economic advantages and amount of time saved for dental technicians.

The development of implantology and the use of biomaterials known to be difficult to weld (i.e., titanium) increased the need for further research in the field of laser welding. This technology became more effective in the 1990s with the industrial improvement of compact, high-power-pulsed Nd-Yag laser units dedicated to prosthetic dentistry. Brazing methods still used have shown their limitations. First, brazing involves multiple preparation steps to modify or repair prostheses, and each step can be a source of distortion and misfit. All those inconveniences disappear with laser welding, because the dental technician is allowed to carry out the assembly quickly and directly on the master cast. Inaccuracies and distortions due to the duplicating process of the model are reduced. The welds are precise and well defined, because the energy is focused on a very small part of the dental framework. The high temperature leading to a weld composed of a fine nugget affects only a small area around the weld and gives a slight heat affected zone (HAZ).[2] As a consequence, welding very close to acrylic resin or ceramic veneers is possible with no color damage. Moreover, the technician is able to control each step of the procedure at any time. Distortion occurring during the welding process can be directly controlled and corrected by the operator with the addition of new spot welds on the opposite side of the initial point of distortion. Conventional brazing does not allow such a control.[3,4] Second, the brazed joint obtained with the use of filler (with a different chemical composition and a melting point lower than the one of the parent metal) can provide oral toxicity due to the release of metallic ions as a consequence of corrosion[1,5,6] and also involves brittleness of the assembly in time. Due to the high temperature delivered by the laser, the use of filler with a similar composition to the parent metal is achievable: the chemical stability of the weld should be increased. To preserve the metal composition and homogeneity, the process parameters of the laser have to be adjusted to prevent the vaporization of volatile alloying elements and keep the corrosion resistance constant compared to the base material. It is currently accepted that if those conditions are reached, the mechanical properties should not be affected.[7-9] This last point leads us to state that utmost care must be taken by the operator to get a reliable joint for any kind of dental alloy used in prosthetic dentistry.

The aim of this paper is to point out each key parameter involved in the laser-welding procedure and to propose solutions to adjust them to provide the production of an optimal dental assembly: smooth surface, full welding depth, without defects (i.e., cracks, porosities). Metallurgical effects are briefly discussed, and a welding procedure is proposed. This procedure can be adapted to gold alloys, semiprecious alloys (PdAg), and nonprecious alloys (Ti, NiCr, CoCr).

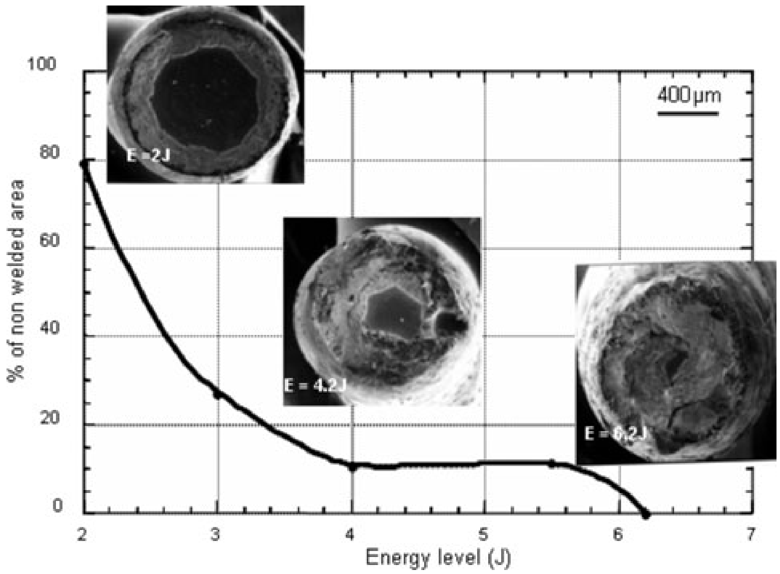


Figure 1 Influence of energy enhancement on percentage of the welded area for orthodontic wires, 1.1 mm in diameter ([NiCrFe Cr 18.26%, Ni 11.22%, C, Si, Mn, S, P, and Mo <1%, Fe cplt], Nichrominox). Welding parameters: $p = 1$ KW, t (ms) = 2; 4.2; 6.2.

Operating laser conditions

The interaction between laser and material is very complex, involving a combination of many parameters: the operating laser conditions (energy, pulse duration, pulse repetition rate, pulse shape, peak power, focal spot size, protection of the welding environment under an argon shielding atmosphere) the diverse varieties of metallic alloys used in dentistry (precious, semi-precious, nonprecious), and the technical aspects of the welding modus operandi, including operator training, metal preparation, the gap between the two parts, and the design and composition of the filler. A lack of knowledge in one of these points will generate degradation of the weld quality and failure of the assembly.

The deepest and finest welds can be obtained with a good selection of laser parameters.[10–13] At least seven parameters are currently available on pulsed Nd-Yag lasers intended for dental technicians.

(1) The laser peak power (P) delivered by the laser device corresponds to the density of energy delivered per unit of time (J/s or Watts). An increase in power overcomes the thermal diffusivity and reflectivity of the material, but the possibility of liquid material projection also increases. This P value has to be limited for welding to avoid defects such as cracks and porosities. Limitation depends on the welded alloy.

(2) The pulse duration is the length of time of a pulse. It can be set from 0.5 to 20 ms according to each metal's thermophysical properties. Because a laser beam needs to be concentrated for a long time on the same point to provide a good welding depth, low thermal conductivity is not considered a limitation; however, an increase of pulse duration can lead to heat diffusion phenomenon, to distortion artifacts, and to the vaporization of alloying elements. When alloys present good thermal conductivity (as for gold alloy), the pulse duration must be reduced. The longer the pulse duration, the deeper the weld rises, and the more the thermal diffusion process may extend in the metal parts, increasing the HAZ area and the weld diameter.

(3) The pulse energy (J or W/s) delivered per pulse is the relation of power (kW) to pulse duration, t (ms)

$$E = P.t$$

To limit cracks and intense metallurgical changes (i.e., intense hardening), the pulse energy must be optimized in correlation with the optimization of the two previous parameters (power and pulse duration). An accepted idea is that deep welding requires an increase of the energy output.[14] Figure 1 shows a micrograph of a transversal section of an orthodontic NiCrFe wire (Nichrominox, Lyon, France) welded without filler with an overlapping multispot technique [P = 1.0 kW; t (ms) = 2; 4.2; 6.2]. The more the energy level rises (all other parameters fixed) the percentage of nonwelded area decreases as expected. Results should be similar in terms of welding depth if the pulse duration has been fixed and the power increased. Baba and Watanabe[14] tested five dental alloys and showed that with a pulse duration fixed to 10 ms, an increase of the voltage of the laser increased the pulsed energy and increased the penetration depth. But if the peak power used is too high, the major risk is creation of dig spots on the surface due to ejection of the liquid sideways as well as high disturbance of the molten area into the keyhole with porosities or voids in the bottom of the weld.[15]

The comportment of each dental alloy is different during laser welding according to the alloy's thermal conductivity and thermal absorption to the Nd-YAG laser wavelength, to its chemical composition, and to the preparation of its surface (rough, sand-blasted, or polished). All those parameters must stay clearly in the operator's mind to adjust the energy output. In Figure 2, the conditions leading to 100% welding area have been studied on a NiCrFe alloy for orthodontic wires, 1.1 mm in diameter (Nichrominox®). The energy output delivered by the pulsed Nd-Yag laser used (Haas Laser Corporation, Schramberg, Germany) is fixed to 6.2 J. Power and pulse duration can vary to keep this energy value unchanged. A combination of power $P \leq 1.0$ kW and pulse duration set around 7.0 ms gives the

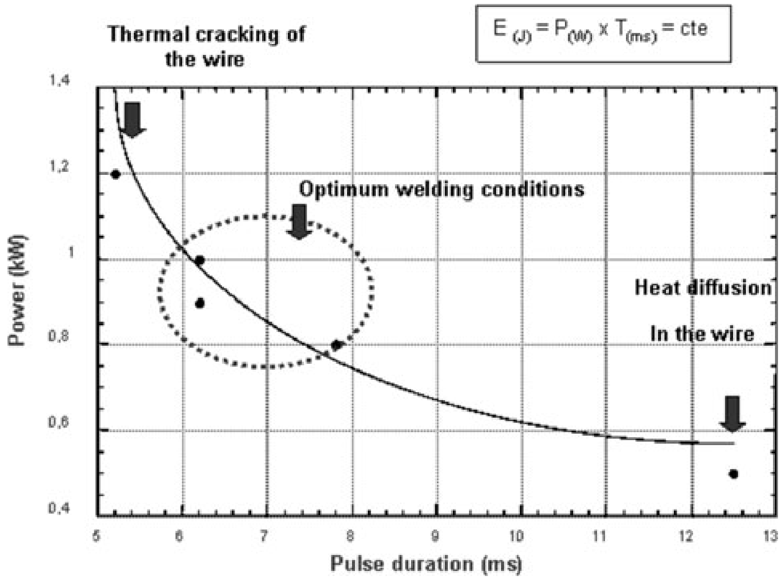


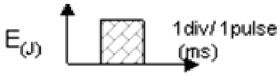
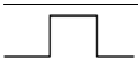
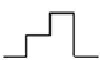
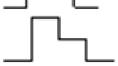
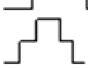
Figure 2 Influence of the adjustment of power and pulse duration for the conditions leading to 100% welding on orthodontic NiCrFe wires (Nichrominox), 1.1 mm in diameter with a low thermal conductivity.

best results for this alloy. When the power is increased and the pulse duration reduced, 100% welding is achieved, but the laser impact is too strong. A part of the metal is ejected, and cracks appear in the weld. In contrast, when the power is decreased and the pulse duration increased, the metal is submitted to an excessive heat transfer and cannot provide a fully welded joint due to a reduced penetration.

(4) The pulse repetition rate (Hz) is the number of pulses delivered per second. For prosthetic applications, a fixed value of 1 Hz allows the operator to meticulously control his/her work during welding, using a multispot process. The heat is delivered spot by spot in the material with 80% overlap to maintain the fusion bath. A short increase of the pulse repetition rate may offer the opportunity to get better control of the multispot overlapping. A maximum of 5 Hz is imposed to keep control of the welding. The influence of this parameter has been illustrated with titanium alloys. According to Bertrand et al,[11] the use of a pulse frequency of 1.0 to 2.0 Hz is optimum. As the pulse repetition rate increases, Ti shows an increase in the Vickers hardness value in the nugget zone. According to Wang and Chang,[16] the use of multiple-pulse laser irradiation on Ti must be associated with a moderate energy flux to minimize surface damage and improve the depth of penetration. No more information concerning the adaptation of the pulse repetition rate is available in the literature for dental alloys.

(5) The pulse shape allows the control of the pulse peak power and pulse duration in real time. It has also been engineered to produce special heating and cooling regimes to control the weld thermal cycle. All experiments described previously were conducted with only the rectangular shape available on primary laser devices. Now some manufacturers propose different pulse shapes and give recommendations for their use as a function of the alloy welded. Table 1 summarizes the different pulse shapes available on the pulsed Nd-Yag laser device (Titec Mark Uno 65, Orotig, Verona, Italy) and the type of material welded, based on the manufacturer's recommendations.

Table 1 Different pulse shapes available on the Nd-Yag laser Titec mark uno 65J (Orotig)

	Classification	Manufacturer indications
	Basic rectangular pulse shape available on all pulsed Nd-Yag lasers	Required for pure metals and titanium
	Ramp-up pulse shape	For precious alloys and reflective alloys
	Ramp-down pulse shape	For CoCr alloys and AgPd alloys
	Double-ramp	For the joining of hybrid alloys
	Double short pulse	For increasing the weld depth

Ongoing research suggests that changing the laser pulse shape also improves the weld penetration and quality for difficult welding materials, such as reflective materials or materials sensitive to cracking and porosities.[15-19] Matsunawa et al[15] describe the effectiveness of laser-pulse shaping in eliminating weld defects in the pulsed Nd-Yag laser welding of aluminum alloys. Our experience in the use of different pulse shapes on Ti,[11] CoCr,[18] or PdAg[20] has shown that an inappropriate choice of the pulse shape can considerably affect the final quality and the mechanical properties of the assembly.

(6) Focal spot size (0.3 to 2.0 mm). The choice of the focal spot size determines the diameter of the laser beam applied on the surface of the material. The focal spot size is correlated with the fluence, $\boldsymbol{\rho}$ (J/cm^2), which is defined as the pulse energy over the irradiated surface.

$$\frac{\mathrm{Pt}}{\Pi(\mathrm{d}/2)^2}$$

This parameter ($\boldsymbol{\rho}$) is very important for pulsed laser processing and welding. When a deep or a narrow weld is required, the operator chooses a small focal spot size (0.3 to 0.8 mm in diameter). The use of a larger spot size (1.0 to 1.4 mm) for an identical given energy reduces the fluence and thus the penetration. Such a process is used for smoothing the weld surface and obtaining an esthetic aspect. If a larger weld is required, to keep a high penetration in the work piece, the spot size must be raised to 1.0 mm, and the energy level must also be increased. But metallurgical changes can occur. For a prosthetic welding procedure, the choice of a focal spot size set from 0.4 to 0.6 mm gives good results.[11] Providing similar effects is possible if the operator keeps the same focal spot size during all welding operations and plays with the position of the focal spot. If the focal spot is defocalized 1 mm above the focalized point, the energy level decreases, and the heat is lower; this position may be used for smoothing the weld bead. If the position of the focal spot is 1 mm beneath the focalized surface, the energy is higher and increases the welding depth. According to Cicala,[19] having a focal point located at the surface of the metal is one of the parameters to provide the best weld stability and prevent cracks in the nugget if other parameters are adapted too.[21,22]

(7) The welding environment in the laser chamber must be free of contaminants. The use of an Argon shielding atmosphere during laser welding is essential to prevent porosities and minimize oxidation on the area surrounding the spot.[23] This is the most important parameter in the welding of Ti, which is very sensitive to the presence of hydrogen, nitrogen, and oxygen during welding.[23,24] For Ti, the spot appears blue if oxidation occurs in the joint (TiO_2), yellow if nitrogen reacts with the metal (TiN), and when the flow of argon is correct, the surface turns shiny gray.[11,24] This is qualitatively validated by the operator under the optical microscope in the laser chamber. The nozzle system depends on the manufacturer configuration and is mostly directed 5 mm on top of the surface. The gas pressure is currently adjusted to 2 bars flow pressure for good protection of the surface as well as a free-hole final surface.[13] If a change in the color aspect of the spot is detected, particularly on Ti, the time during which the molten pool must be protected is increased, and the gas density must be increased as well, with consequences on the surface aspect before smoothing. Once more, the influence of operator skill is a key parameter. Argon gas must systematically be used to clean the surface before welding and avoid pollution of the melting area during welding. Protection of the focal lens from ejection of the metal, hunting of the formation of plasma on the surface of the molten area as well as increase of the penetration of the laser seam into the work piece by mechanical gas pressure are also positive consequences of gas protection.[23]

The influence of the above parameters is often underestimated. The mechanical properties and corrosion performances of the welded joints can deteriorate because of a noncontrolled process.

Metallurgical effects of laser welding

Because microstructure determines material properties, it is essential to understand and control its formation. The solidification microstructure depends on the local solidification conditions, themselves depending on heat and mass transfer in the system directly correlated with the process parameters and the material composition. So, independent of the metal thickness, the welding condition adjustments must take into account thermal, metallurgical, and mechanical aspects of each alloy as well as their absorptive properties to the Nd-Yag laser wavelength. Table 2 summarizes the thermophysical properties of chemical elements in the composition of dental alloys.[25]

Gold alloys are easy to weld thanks to their excellent thermal conductivity, but they have a poor thermal absorption due to their high reflectivity to the Nd-Yag wavelength. As a consequence, a high-energy output (a high peak power associated with short pulse duration to prevent overheating and large heat diffusion) is required.[14] As suggested by Watanabe et al,[13] the use of a black marker on the surface is a solution for decreasing reflectivity before welding.

NiCr and CoCr alloys are less reflective than gold alloys but present a lower thermal conductivity. To weld, a lower

Table 2 Comparison between physical properties of the main chemical elements used in dentistry[14,25]

	Gold alloys	Ti alloys	CoCrMo	NiCrMo	Pd alloys
Thermal conductivity (W·cm^{-1}·deg^{-1})	Au = 2.97 Cu = 3.95	0.17	0.142	0.117	Pd = 0.72 Ag = 3.97
Melting point	1064°C	1668°C	1340°C	1240°C	1100°C to1260°C
Coefficient of absorption to the Nd-Yag wavelength	Au = 0.03 Cu = 0.06 Pt = 0.27	Ti = 0.4	Co = 0.32 Cr = 0.40 Mo = 0.40	Ni = 0.32 Cr = 0.40 Mo = 0.40	Pd = 0.26 Ag = 0.03

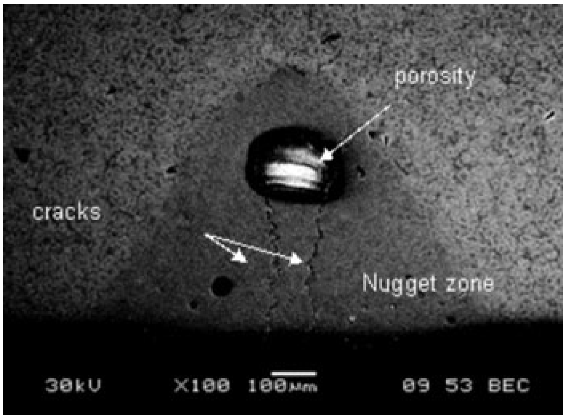


Figure 3 SEM examination of a cross-sectional view of a single laser spot applied on a Pd-Ag alloy plate "Callisto 60" Ivoclar, Lichtenchtein.

energy output is used, and a medium power rate associated with long pulse durations is required to overcome poor thermal conductivity.[25,26]

The welding of Ti has been widely studied.[16,24,27-32] Titanium alloys need a lower energy density than gold alloys, due to their excellent thermal absorption to the Nd-Yag laser wavelength. The major problem consists in their sensitivity to oxidation or nitriding during heating, which tends to harden titanium's surface and weaken the final joint,[24,28] resulting in brittle welds. This problem is increased with the decrease of Ti alloy purity. Covering the welding area with an inert gas such as argon or helium minimizes these contaminations in the laser chamber.[24] The set of short-pulse durations is required to reduce a probable overheat of the metal. To compensate, a high peak power is selected to get the appropriate energy level. The use of titanium filler is necessary to compensate for the ejection of material on its surface due to the use of a high peak power. Independent of the alloy composition, adjustment of unsuitable parameters generates harmful defects, such as internal porosities, voids, and cracks, in the microstructure with significant consequences on mechanical behavior (fatigue and tensile tests) and corrosion.

Porosities

Porosities are detrimental to weld quality and can be found in solidified deep penetration welds.[15] These porosities are gas pores and may vary in size from small bubbles to macro cavities. Porosities forming in pulsed-laser-welding procedures are related to the rapid solidification process and are frequently associated with the use of low welding speeds (a few mm/sec managed by the operator) and low pulse frequencies (1 or 2 Hz). Small bubbles rise in the liquid phase and are entrapped within the solidified metal at the end of the laser pulse. Macro cavities are the results of the rapid solidification of the upper part of the keyhole, which solidifies first, rapidly occluding gas vapors in the lower third of the weld.[33] Additionally, the fusion bath can be contaminated with air, grease, or dampness. As a consequence, the preparation of the two half pieces before welding requires utmost care, and process parameters (gas flow, energy, pulse shape) must be optimized. The pulse shape significantly influences porosity formation tendency in pulsed-laser welding.[33] Kakimoto et al,[34] testing the influence of a rectangular pulse shape on pore formation, observed that porosities were more likely present in spot welds for CoCr alloys than for commercially pure Ti welds.

Cracks

Hot cracks are related to the heat generated during the welding process. The heat impact is so rapid and so localized and the cooling so immediate, that a refinement of the microstructure of the alloy inside the weld nugget is observed, along with a coarse hardening for the majority of alloys.[26] Moreover, the material contracts, creating tensile stress and shrinkage inside the fusion zone during cooling, leading to the crack formation. This phenomenon is dependent on the laser-welding process, the initial microstructure, and the chemical composition of the welded alloy, as well as its contents in gas entrapment. The shielding gas has only a small influence on hot cracking. Hot cracks are localized inside the weld nugget or between the HAZ and nugget zone area and affect joint durability.[26,35] Cracks are frequently initiated from pores (Fig 3). Cool cracks occur at low temperatures. They can be initiated from an incomplete weld or can be due to a bad damping of the half pieces to be assembled. Cold cracks are rather thin, with no oxides on their surface. They have to be avoided because they are the starting point of brittleness and corrosion. An excessively concave surface can promote small cracks appearing at the end of the weld process, propagating in the weld bead. Their prevention consists in the use of filler to get a plane surface. To overcome such effects, heat treatment of the material or postwelding treatments of the weld are recommended.

Technical aspects of the welding procedure: a proposal for optimization

Technical aspects of the welding procedure are probably one of the most imprecise parameters of laser welding but are also essential to prevent the defects described above. Each Nd-Yag laser manufacturer gives technical indications concerning the welding procedure to be performed. Dental technicians may apply their own procedure following their own experience. In the literature, the influence of the operator has been clearly demonstrated.[36,37] Bertrand et al[10] have shown that if the operating conditions are optimized, the operator's influence can be minimized. Within the limits of our technical experience in laser welding, some guidelines are suggested

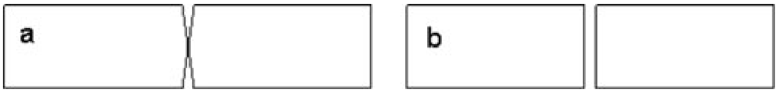


Figure 4 Joint configurations. Seam geometry: (A) X Shape. (B) I Shape.

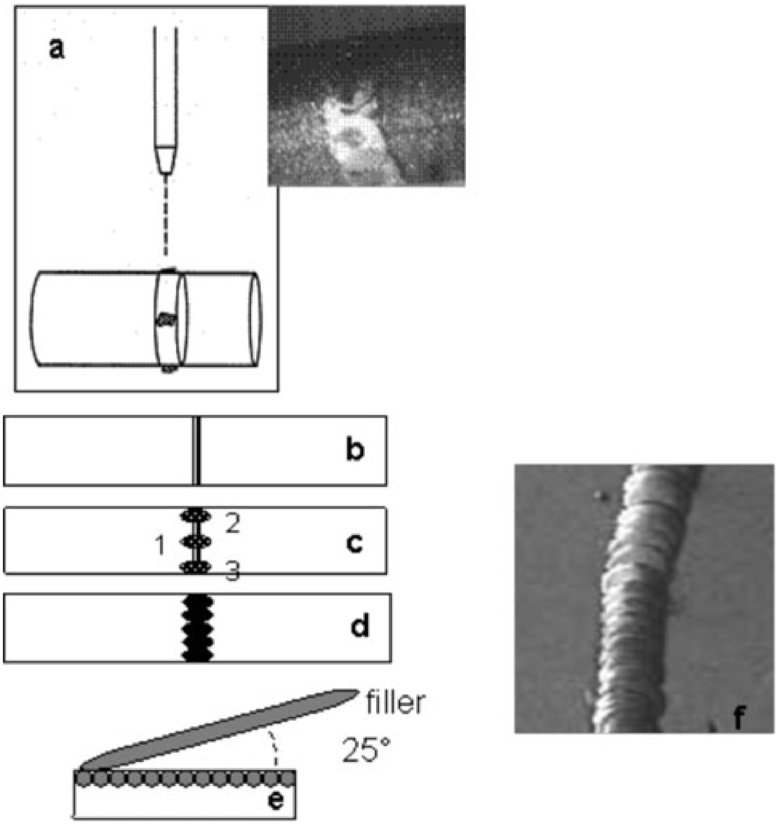


Figure 5 (A) Procedure for welding wire, 2 mm maximum diameter. An optical micrograph shows the external aspect.
(B) Half pieces are butt-joined.
(C) One shot in the middle, one at each end of the plate on both sides are applied to fix the two half pieces and prevent distortion.
(D) A full seam is made with 80% overlap.
(E) Filler may be used if ejection of material has occurred.
(F) A third seam is done to smooth the weld with a larger focal spot size (1.2 mm). All other parameters are unchanged.

(1) Identify the composition of the metal before laser welding. Precious alloys with a concentration of Zinc $\geq$2% or silver $\geq$20% as well as nonprecious alloys with a reduced concentration of boron, carbon, or silicon are known to be difficult to laser weld and are not concerned by the following requirements.
(2) Prepare and cut joint surfaces with a disc under water spray, drawing an "I" shape or an "X" shape (Fig 4) to avoid distortions due to random preparation. The "I" shape is preferred for the welding of small thicknesses and for alloys with good damping and welding properties. The "X" shape is preferred for the welding of large thicknesses, for rods, and when the use of filler is required.
(3) Prepare metallic surfaces as parallel as possible to promote a good laser beam, then sandblast them with alumina powder (0.5 μm), clean them with acetone or alcohol, and hot-air dry them before laser welding. The cleaner the surface (no dirty or greased surfaces), the better the expected results.
(4) Place the dental framework directly on its master cast. The cast is put on an adjustable platform to prevent instability, resulting in the operator's difficulty in keeping focus on the surface of the metal. This keeps his/her hands free to handle the filler during the welding.
(5) Set welding parameters according to the metal composition as specified above, depending on the metal's thickness and thermophysical properties.

A small thickness of the joint (lower than 2 mm deep) requires the use of a narrow contact between the two pieces. The technical aspects of the welding procedure depend on the shape of the work piece.

For wires, one laser shot is done to the four cardinal points with a low energy output to fix the two parts and avoid distortion. Then, with an increase of the energy output compared to the four previous spots, laser spots are applied all around the circumference of the wire with at least 80% overlap to prevent porosities and cracks (Fig 5A). Filler is recommended to compensate for a vaporization of the metal on the surface or if the metal is known to be sensitive to hardening and shrinkage due to thermal stress, as for Ti or PdAg alloys.

For flat surfaces, the two parts are butt-joined with three welding spots with low energy on both sides to prevent distortion: one shot in the middle, one at each end of the plate. Then the energy is raised, and the plates are fully welded on each side with at least 80% overlap. A final pass is used to smooth down the weld with the same parameters but with a larger focal spot size to correct surface defects, such as small cracks near the top, and to get an esthetic aspect (Fig 5B to F).

When more than 2 mm in depth is required, an "X" shape preparation is used, and welding always requires the use of an adapted filler, essential to optimize laser welding, minimize tensions occurring in the work piece, and fulfill the joint (5.0 mm has been measured for implant frameworks). The gap between the two parts of the joint is adapted to the filler diameter. Filler

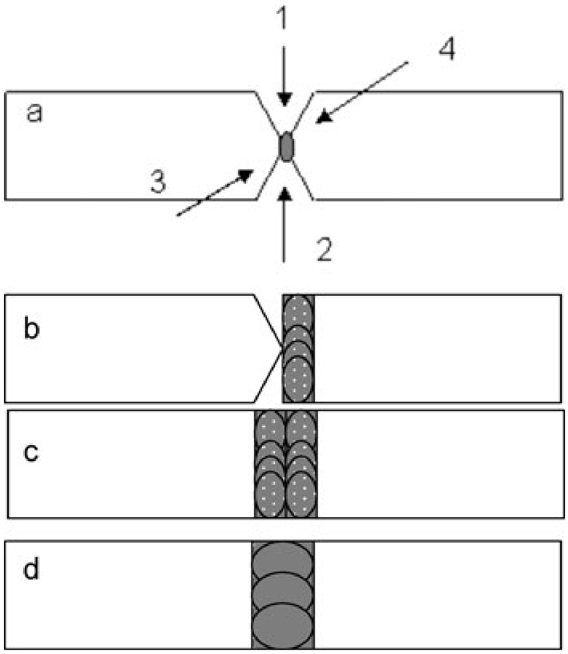


Figure 6 (A) Due to the metal coming from the filler, an intimate contact between the two parts is achieved. The unit is then melted without filler, thanks to four spots shot in opposite position one to the other. (B,C) The filler is deposited on one side of the joint spot by spot, with 80% overlapping, then on the other side. (D) The welded joint is smoothed with a third pass, 80% overlapped, with a larger spot size.

is cleaned with acetone and dried. Welding starts with the making of a full contact in the center of each half piece, thanks to the metal coming from the filler, to provide a narrow contact between the two parts (Fig 6A). The unit created is then melted without filler thanks to four spots shot in opposite position of one another. Next, the filler is deposited on one side of the joint spot by spot, with 80% overlapping, then on the other side (Fig 6B,C). Finally, the focal spot is increased up to 1.2 mm to smooth the surface, with all the other parameters unchanged (Fig 6D).

Whatever the geometry of the pieces to weld, these procedures provide a full weld. The value of the gap chosen before the first laser shot is discussed in the literature. According to Taylor et al,[30] the two parts must be prepared with no gap. For Sjögren et al,[28] the gap has no consequence on the reliability of the joint. For Chai and Chou,[12] the gap should be no more than 0.5 mm maximum to provide a good weld quality; the use of filler is essential, though. Commonly used fillers are round wires of 0.20, 0.35, or 0.5 mm diameter or as flat and thin wire. The use of low diameter filler is preferred, because it facilitates melting.[36] The angle at which the filler must be introduced in the welding pool is important as well.[36] According to Cicala et al,[19] who worked to prevent cracks on Al-Mg-Si alloys, the wire should be placed 25° to the surface, with a uniform compression system and focal point located at the surface of the work piece. This orientation of the round filler facilitates the dumping of the metal in the "X shape" joint. If the filler is flat, it is positioned easily in the "I shape" joint, parallel to the surface of the joint, to facilitate the melting of the filler with each side of the parent metal. At last, when the joint is fulfilled all around the work piece, a smoothing of the weld is achieved by increasing the spot size with the same 80% overlapping. Papers relating to the influence of a multiple welding pass on the microstructure and the future of the joint are inconclusive.[17,19]

Conclusion

The use of a pulsed Nd-Yag laser by dental technicians is a routine procedure and seems to be technically easy to perform with adequate training. That said, better tuning of the experimental parameters can minimize operator influence. Standard guidelines would be helpful to optimize the reliability of the welded joints, because the management of the operating conditions is still empiric. Concerning corrosion and mechanical behaviors in correlation with process parameters, data are missing for many prosthetic alloys except for CoCr and Ti, for which clinical studies relative to the resistance of the welds have been made.[31,32,37] Unsolved technical points remain, for example, the influence of the gap size and the volume of filler necessary to increase the durability of the welded joint. Furthermore, the impact of a multiple welded pass upon the modification of microstructure has not really been studied in the field of prosthetic dentistry, whereas the need for a last smoothing pass is essential to erase surface defects and for esthetic reasons. Statements of laser processing parameters and their effect on weld quality have been discussed in this paper for a large range of dental alloys. The prevention of weld defects such as voids and cracks needs to be controlled to provide more homogenous welds and avoid fatigue failure and/or stress corrosion.[14] Each step of a welding procedure has been described and discussed. An optimized technical procedure available for all dental alloys is proposed to guarantee good quality welds, independent of the welded alloy.

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