Chapter 6

Laser Welding of Different Dental Alloys

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Additional information is available at the end of the chapter

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Abstract

Laser welding permits joining various types of pieces, made of similar or different alloys, as titanium-based alloys, CoCr alloys, and even AuPd alloys. Laser welding is best suited to weld titanium alloys because they have higher rates of laser beam absorption and lower thermal conductivity compared to other dental casting alloys. Compared to micro pulse welding, laser welding is superior, obtaining the welding cord being faster and easier. The success of the welding procedure depends on the operator's dexterity and the choice of the welding parameters. Selecting the best combination of pulse energy, pulse duration, and peak power for each welding step is decisive.

Keywords: laser welding, micro pulse welding, dental alloys, welding assessment, welding cord

1. Introduction

Welding in dentistry involves small metallic areas, often in the proximity of resin or ceramic structures, which may be damaged by heat (**Figure 1**). The fracture of a metallic frame usually happens in an area of minimum resistance. This type of damage could not be repaired 15–20 years ago, using welding systems available at that time.

Nowadays, two types of welding are suitable for use in dental technique: laser and micro pulse [1].

After Nd:YAG lasers appeared in Europe, in 1990, laser welding has been extended to dental technique and permits joining various types of pieces, which might have been difficult or even impossible to do with other techniques.

Figure 1. Laser welding of a fractured clasp and frame.

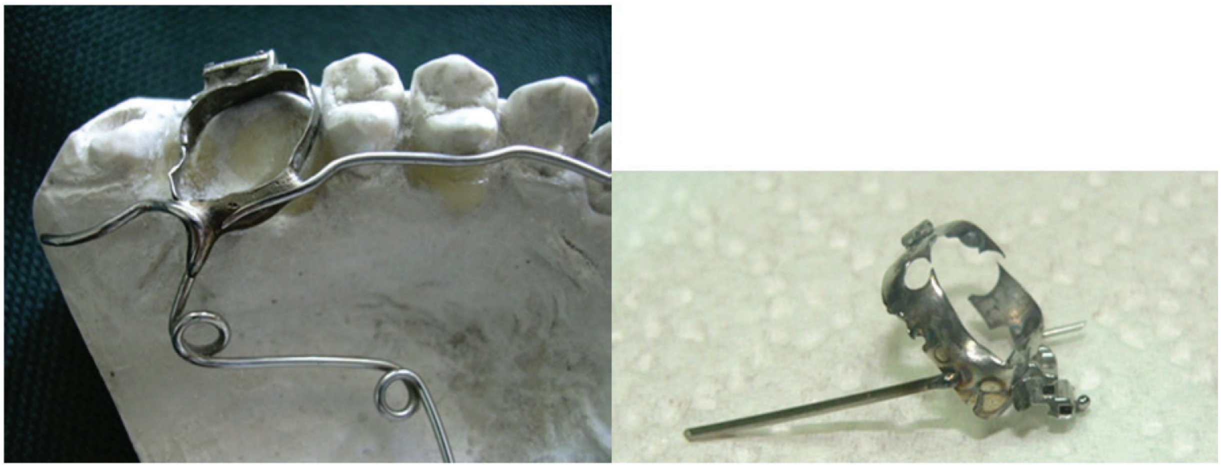

Figure 2. Welded CrNi stainless steel orthodontic ring and wire.

It permits joining similar or different alloys, as titanium-based alloys, CoCr alloys, and even AuPd or CrNi stainless steel alloys (**Figure 2**).

In laser welding, heating and melting are limited to a small area, which prevents damaging the components of the denture pieces which might deteriorate when heated (resins, ceramics) (**Figure 3**). It permits the welding of elements situated in places difficult to reach, such as the inner parts or extremely small, delicate, and sensible elements. It is very efficient in repairing the framework of removable partial dentures, being fast, economic, and very accurate [2].

It may also be used for manufacturing removable partial dentures, by joining pieces which might be difficult to cast in one piece, due to various reasons, such as high contraction at casting. One of the main advantages of the method is that of "cold" welding, on a model or even in hand. Nowadays even "in-mouth welding" is possible [3].

All laser welding devices used in dental technique are equipped with an optic enlarging system which permits perfect visualization of the fragments to be welded (**Figure 4**), the space between them, and the position of the filler metal, when used. The filler metal (special wire for laser welding) is the same type as the base material and has to be used when there is some space between the two pieces to be welded. Welding without a filler material may be carried out when the distance between the two pieces to be welded is almost imperceptible [4].

Figure 3. Welding of a fractured clasp in close proximity to the saddle made of an acrylic resin.

Figure 4. XXS laser welder for dentistry (Orotig) and its enlargement system.

Laser welding in dental technique often uses a protected environment, argon 4.6 with a purity of 99.996% or argon 5.0 with a purity of 99.999%, in order to prevent the oxidation of the alloys [4].

Laser welding may be done in continuous or pulsed mode. The parameters which may be modified in case of welding with a Nd:YAG laser, in a continuous emission mode, are the radiation power, the welding speed, and the diameter of the laser beam. The radiation power variation is limited by the manufacturer and does not have a great influence on the welding depth. The diameter variation of the laser beam is also limited, in order to obtain the minimum density of the energetic wave; consequently, the only parameter which may significantly influence the morphology of the welding is the welding speed. A low welding speed does not necessarily imply a greater welding depth. In case of noble alloys, optimal welding speed is considered to be 10.1 cm/min, and it doubles in the case of base metal alloys: 20–25 cm/min. These parameters permit a welding depth of 0.8 mm for noble alloys and up to 2.0 mm for base metal alloys. Variations by 20% of these parameters may lead to incomplete welding (too high speed) or uncontrolled melting, which may compromise the entire piece [4].

In case of Nd:YAG laser welding pulsed mode, the density of the energetic flux is at least 10 billion times greater than when using the continuous mode. The exposure time is very short, so the thermal conductivity of the alloy is of less importance. In this case, the morphology of the welding is influenced by the impulse energy, length, and frequency. In case of high energy density, the side effects which appear in the welded structure may not be generalized [4].

The action of the laser beam that leads to the formation of the welding cord can be described as follows (**Figure 5**):

- The material is first heated by conduction.
- The absorbed energy superficially penetrates the alloy, melting the impact surface.
- A metallic vapor develops in the center of the impact point. The material partly absorbs and diffuses the energy of the beam.
- The vapor pressure increases and dispels the melting alloy to the periphery of the beam and upward. This results in creating a narrow (capillary) shaft which propagates through the material. This shaft, with a diameter barely greater than the beam, is physically filled by metallic vapor plasma. Its walls are coated with a film of melting metal maintained by capillarity.
- The melting metal is finally sent backward and closes the welding cord (**Figure 6**) [5, 6].

The quality of micro pulse welding is comparable to that of laser welding. It has the advantage of a lower initial investment, but it uses electrodes that are consumed in time and have to be replaced. When compared to laser welding, micro pulse welding appears to be more visible and embossed (**Figures 7** and **8**). The probability of developing pores is higher, compared to laser welding, which is much more compact [7].

Welding in dental laboratories is made by melting small surfaces of the metallic piece. Each time, a welding cord with overlapped spots will be obtained (**Figure 6**). The area in close proximity, named thermally affected area (TAA), is very sensitive to thermal variations after welding, as sudden cooling of the material, which might lead to cracks. The TAA is usually tougher than the base material (BAA), from which the welded piece is manufactured.

The quality of the welding depends on the alloy's nature, the welding mode, and the laser's parameters [4].

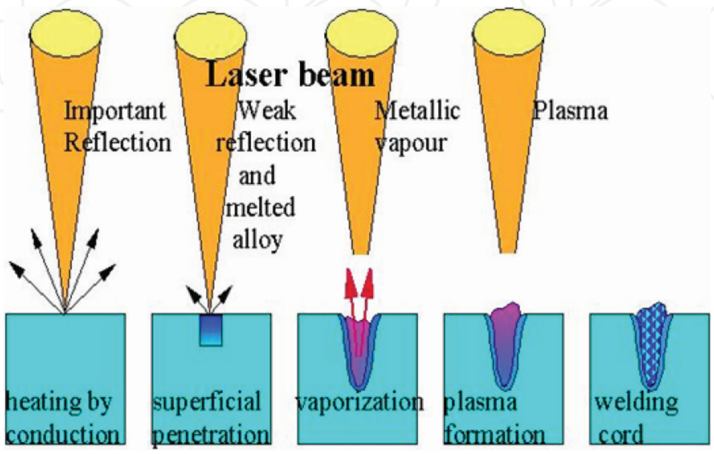

Figure 5. Stages of the welding cord formation.

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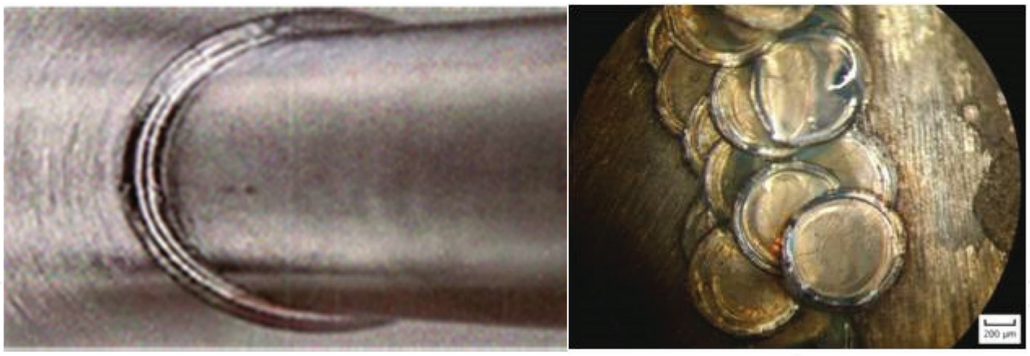


a. b.

Figure 6. (a) Image of the welding cord. (b) Microscopic image of the welding points.

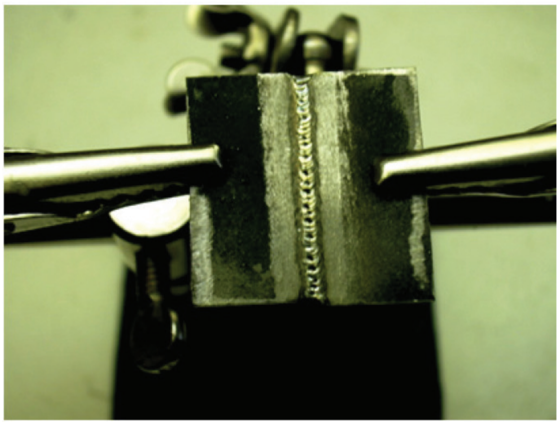
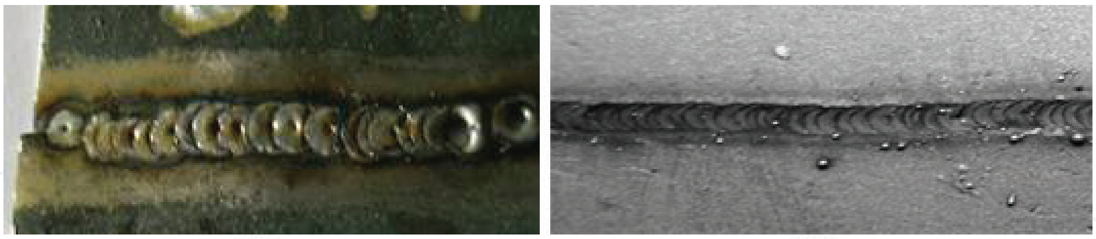


Figure 7. Micro pulse welded piece.



(a) (b)

Figure 8. Appearance of micro pulse welding (a) compared to laser welding (b).

The quality of laser welded joints for different dental alloys may be evaluated by different invasive methods, metallographic analyses and microhardness testing, and noninvasive methods, dye staining, X-ray, and microscopy [8, 9].

2. Welding of TA6V4 and AuPd alloys

The TA6V4 alloy is a titanium-based alloy containing 6% aluminum and 4% vanadium, mainly used in manufacturing ready-made pieces for implantology.

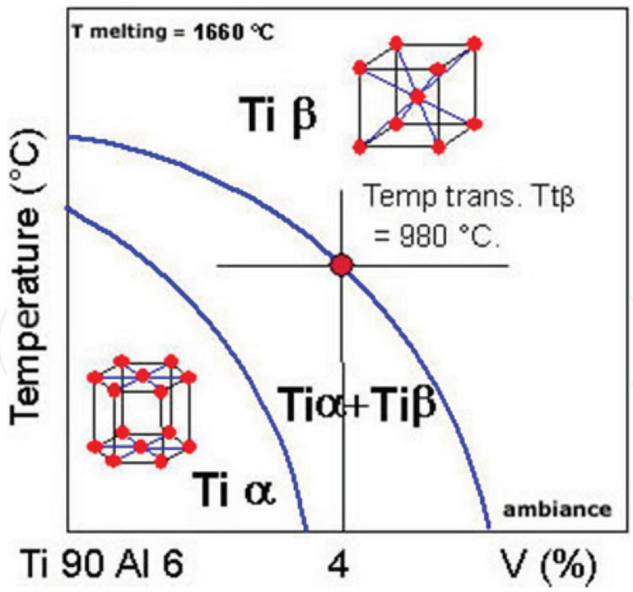


Figure 9. Schematic pseudo-binary phase diagram of TA6V4 alloy.

The alloy is biphased Tiα + Tiβ, at room temperature, with a slight phase percentage for Tiβ, as shown in the pseudo-binary phase diagram (**Figure 9**). The existence of the two phases Tiα and Tiβ, at room temperature, enables creating an alloy with a high mechanical resistance, due to the mutual interaction of the two phases. The alloy has an elasticity limit of 875 MPa.

During heating, the Tiα turns into Tiβ at approximately 980°C. During fast cooling, the Tiβ phase undergoes a so-called martensitic transformation forming a complex lamellar structure inducing significantly altered mechanical properties. These mechanical properties will be recovered by a low-temperature thermal treatment.

This alloy welds mainly to itself or to other alloys by laser welding. Metallurgic analysis, by metallography and scanning electron microscope (SEM) observation, after a single impulse

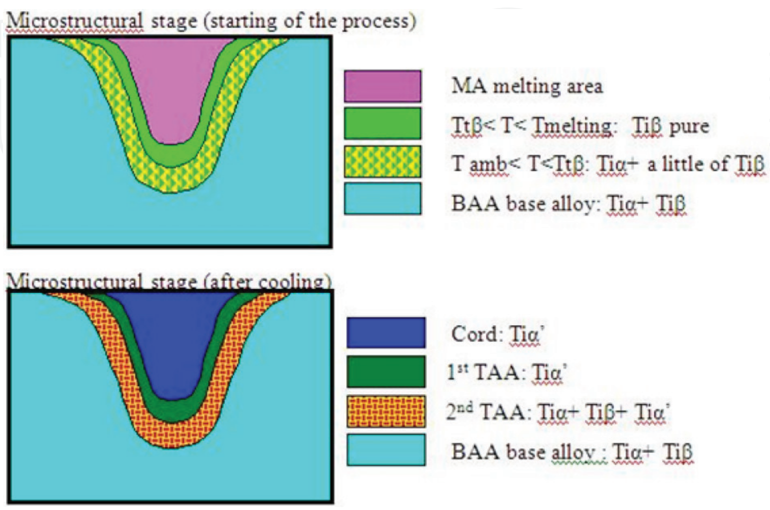


Figure 10. Schematic description of the cord during welding.

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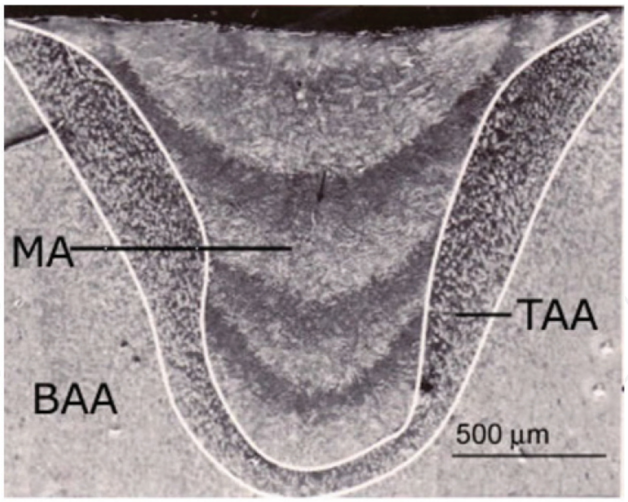


Figure 11. SEM observation of the TA6V4 cord sample after a single impulse laser impact.

laser impact, of the sample is characterized (**Figures 10** and **11**) in the following way: after cooling, there is a melting area (MA), a thermally affected area (TAA), and an area corresponding to the base alloy (BAA) [10].

- The MA is mainly formed of Tiα turned by martensitic transformation into Tiα'.
- The TAA is mainly composed of two sublayers developed in the proximity of MA, formed of a Ti″ structure and, deeper down, of a complex Tiα + Tiα + Tiα' structure.
- The BAA consists of the Tiα + Tiβ structure.

The AuPd alloy welded by laser technique is the standard Qualibond 2 (PX Dental/Qualident) alloy for the metallo-ceramic technique, containing 51.2% Au, 38.6% Pd, indium, gallium, and ruthenium as additional elements.

For the AuPd alloy for the metallo-ceramic technique, **Figure 12** shows the successive impacts leading to the welding of the two pieces. Like in the case of a titanium-based alloy, there is a very perturbed TAA (**Figure 13**) and a lamellar structure of the MA (**Figure 14**).

In case of TA6V4 alloy, the cooling speed plays an important role on the mechanical characteristics due to its influence on the phase transformation structures into a solid state. The elasticity limit during high temperatures decreases, and the resistance to wear is rather unaffected by laser welding due to the fact that the cord has no porosities or other defects (cracks, snaps) [11].

In case of the AuPd alloy for the metallo-ceramic technique, it appears the fracture toughness of the laser welded area is higher than in the case of brazing. On the other hand, the wear resistance of the laser welding is lower than in the case of brazing (**Figure 15**).

The quality of the welding is mechanically satisfactory. In order to avoid problems, initially, both parts of the joined piece should be subjected to low-level energy impacts, followed by greater energy for filling. The success of the welding procedure also depends on the operator's dexterity and the choice of the welding parameters [12].

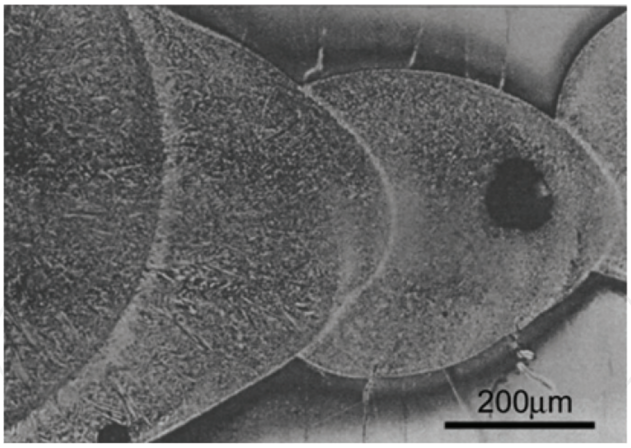


Figure 12. Welded area (SEM).

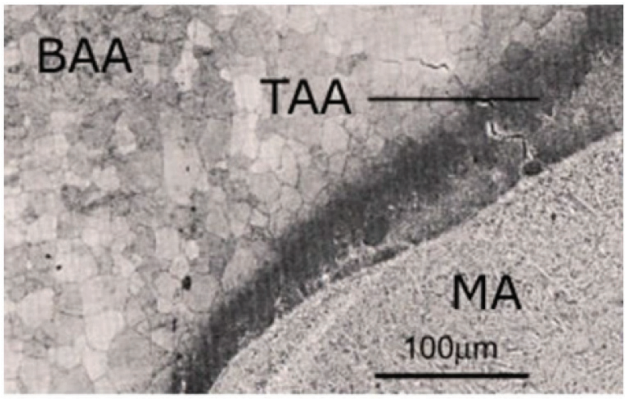


Figure 13. MA, TAA, BAA areas (metallography).

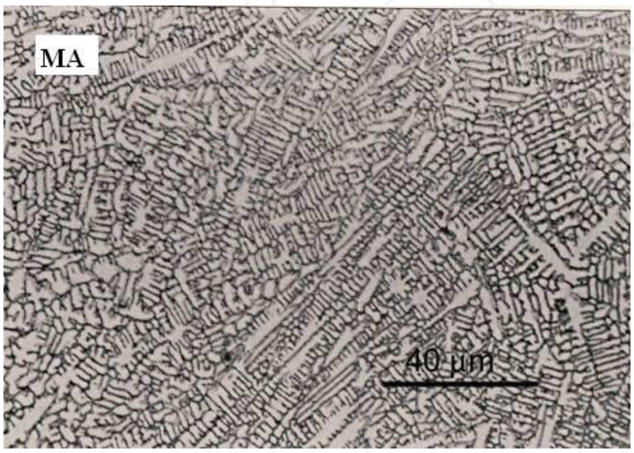


Figure 14. MA area (metallography).

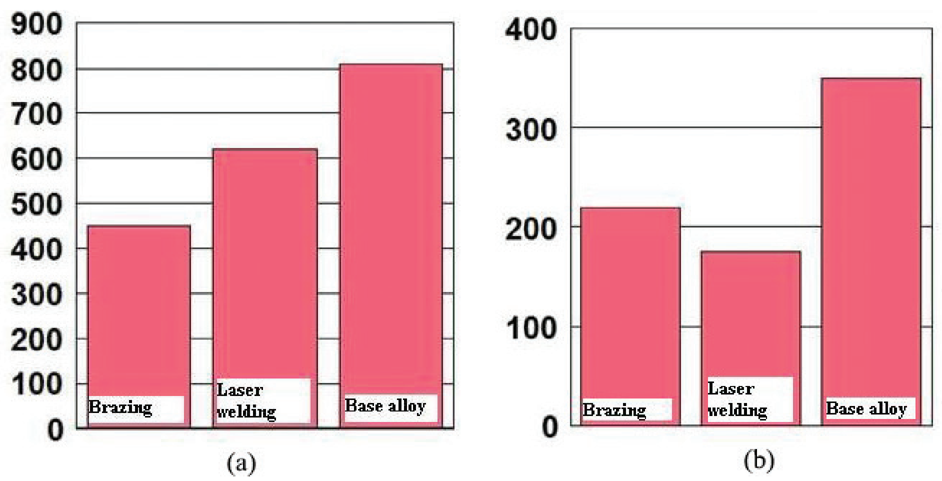


Figure 15. (a) Fracture toughness (MPa). (b) Resistance to wear (MPa).

3. Welding of three different CoCr alloys

Three different CoCr alloys, frequently used for manufacturing metallic frameworks of removable partial dentures, were tested: Heraenium CE (Heraeus Kulzer), Wironit Extra-Hard (Bego), and "C" alloy (Vaskut Kohàszati Kft). The chemical composition and mechanical properties of the alloys are shown in **Table 1**.

The alloys were analyzed both in the form of metallic frameworks of removable partial dentures (**Figure 16**) and as metallic casted plates with dimensions 10x20mm and thickness of 0.4 mm (**Figure 17**). For improving the structure of the alloy plates, heat treatments at different temperatures were applied.

In some cases, the use of a filler metal, special 0.5 mm diameter CoCr Finalloy filler (Fino), was needed (**Figures 18** and **19**).

The equipment used for welding consisted of Welder micro pulse (Schütz Dental) and Laser 65 L-Titec (**Figure 20**).

Welded joint quality was tested by radiographic, microscopic, metallographic, and micro-hardness tests [13].

In order to assess the quality of the welded joints and visualize possible structural defects as cracks in the base materials, X-rays and microhardness tests were carried out. The inverted

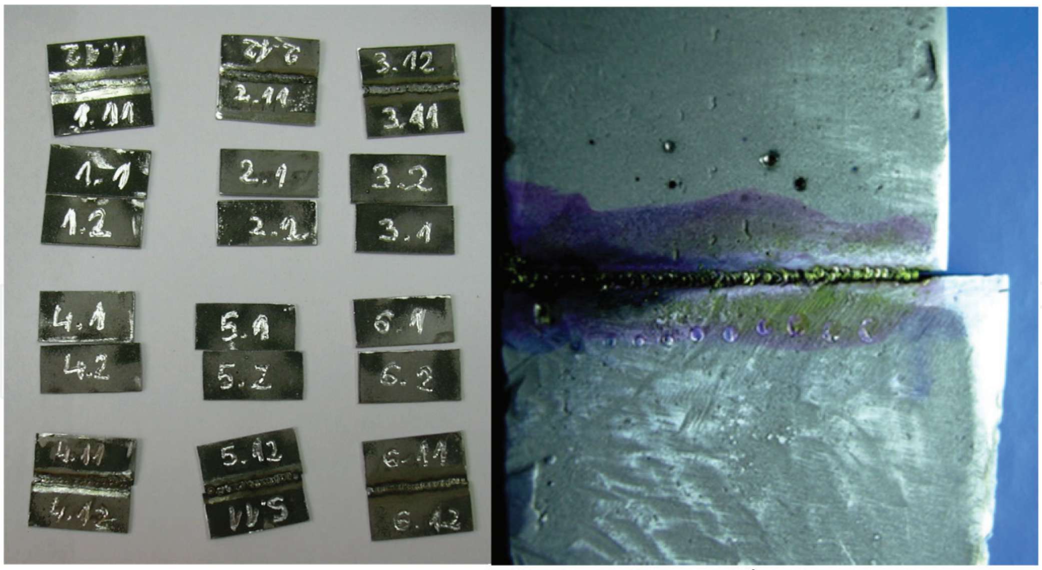
Tested alloys	Co	Cr	Mo	Si	Mn	C	Tensile strength R_m	Vickers hardness
Heraenium CE	63.5	27.8	6.6	1.0	0.6	—	890 N/mm^2	380 HV
Wironit Extra-Hard	63.0	30.0	5.0	1.0	1.0	<1.0	910 N/mm^2	385 HV
"C" alloy	65.0	29.0	5.0	0.35	5.0	0.4	760 N/mm^2	380 HV

Table 1. The chemical composition and mechanical properties of the three alloys.

Figure 16. Some fractured metallic frameworks of removable partial dentures, before and after welding.

metallurgical microscope and the stereomicroscope enabled the observation of different processing aspects of the metallic components, relevant for the welding procedure.

Microhardness analysis was carried out using a 100 g charge, five to six impressions for each area of the welded joint being made, and shows a small increase of the hardness in TAA and



a. b.

Figure 17. (a) The casted plates. (b) Plates after welding.

MA. The hardness in the MA shows values between those of the BAA and TAA. Microhardness values of the welded joints are up to 15% lower in the TAA for Wironit Extra-Hard (Bego), with no heat treatment, and higher up to 16% if heat treatment was made.

In case of Heraenium CE (Heraeus Kulzer) microhardness, part of the samples without heat treatment shows no changes in the MA and TAA; part of the samples shows decreased values up to 25%. Samples which had undergone heat treatment show no changes.

In case of "C" alloy (Vaskut Kohàszati Kft), part of the samples shows no microhardness changes; part of the samples shows decreased values up to 33%.

These values are of no great importance as microhardness variations may appear due to lack of homogeneity of the casted base alloy [14].

X-rays show casting defects, such as lack of material and cracks within the base material (BAA). A radiotransparency on the welding line and some imperfections in the clasps welding area may be observed (**Figure 21**).

For the "C" alloy (Vaskut Kohàszati Kft), the welding area, dyed in yellow, shows no fissures in the immediate vicinity of the welding, in the TAA, because the laser was used at very low temperatures and there are no contractions in the analyzed material. However, X-rays show radiotransparency in the MA, which indicates a superficial fusion which does not cover the entire thickness of the plate. (**Figure 22**) Despite the fact that the plates used are not very thick, welding does not cover the whole depth. This results in the fragility of the welding [11, 13].

Microstructural analysis presents the relative homogeneous dendritic structure specific for casted alloys, nonmetallic inclusions, and some chemical compounds. Intergranular precipitations and spherical shape compounds, consisting of alloy's elements, placed inside

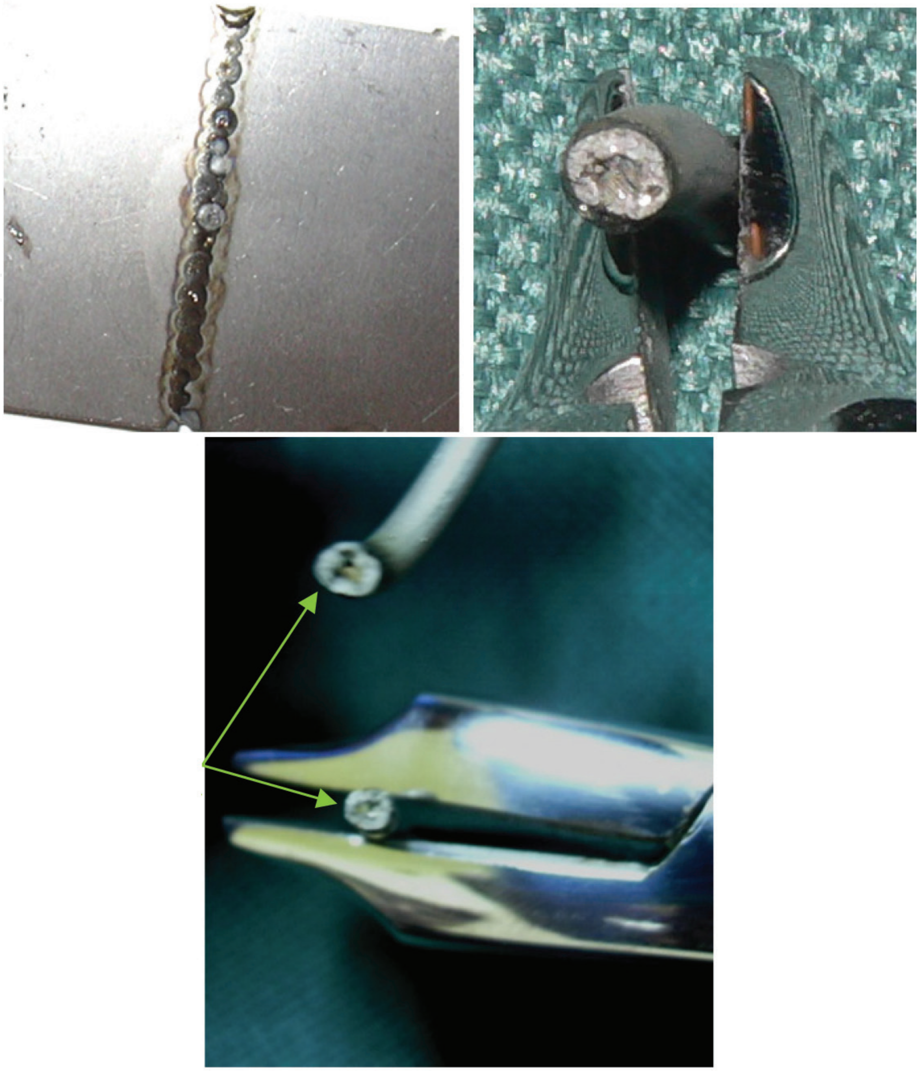


Figure 18. Laser welding without filler metal.

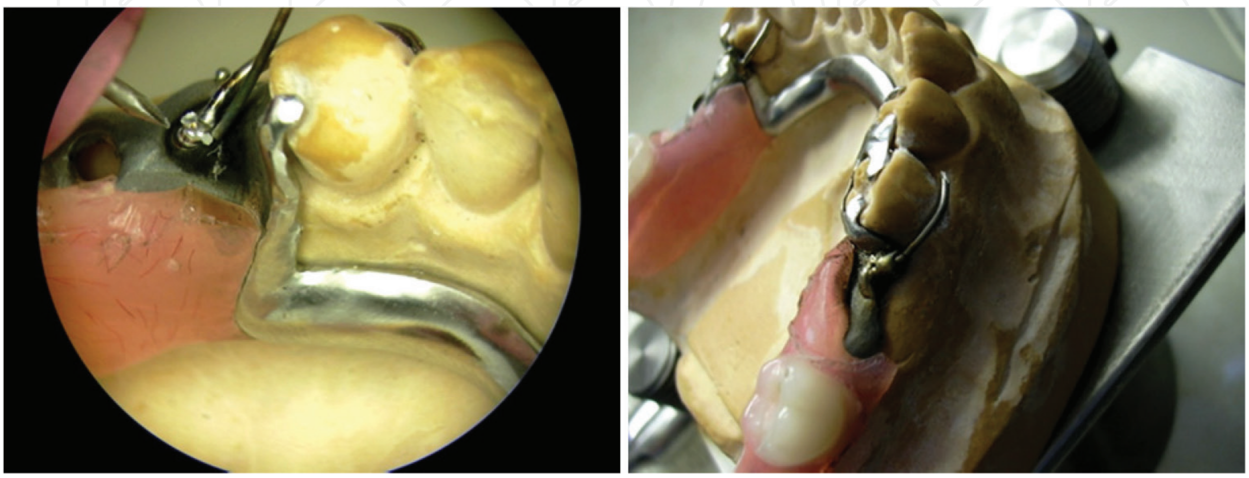
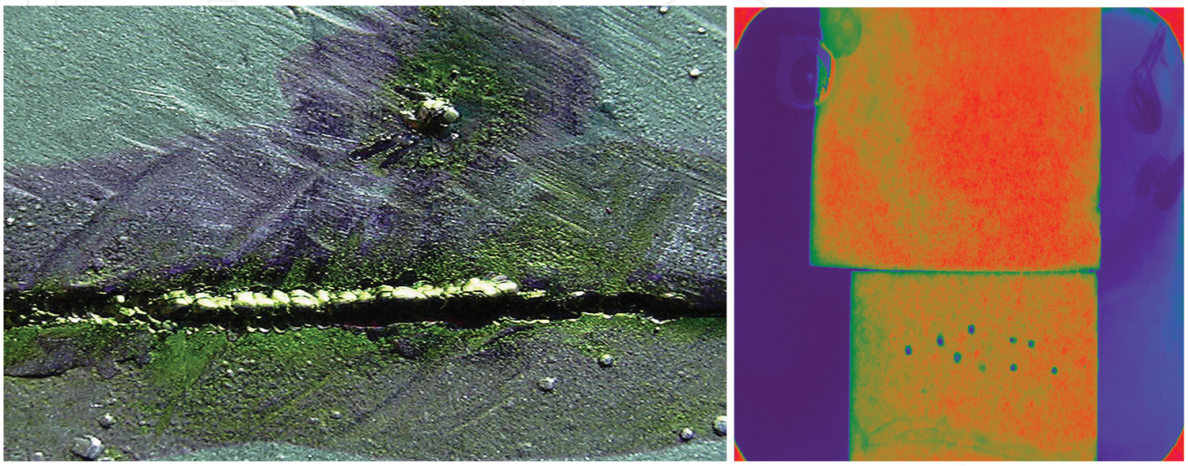


Figure 19. Laser welding with filler metal.

Figure 20. The micro pulse welding device Welder (Schütz dental) and laser 65 L-Titec with welding parameters.

a. b.

Figure 21. Radiographic images: (a) Metallic framework. (b) Welded plates.



a. b.

Figure 22. Assessment of the welded "C" alloy (Vaskut Kohàszati Kft) area: (a) Basic fuchsin dye staining. (b) X-ray pseudo-chromatization.

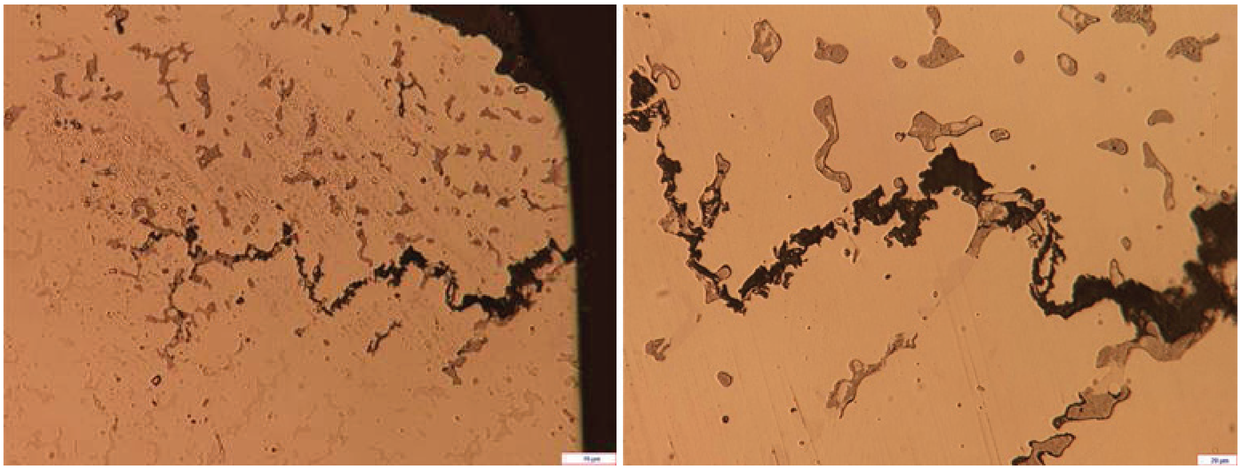
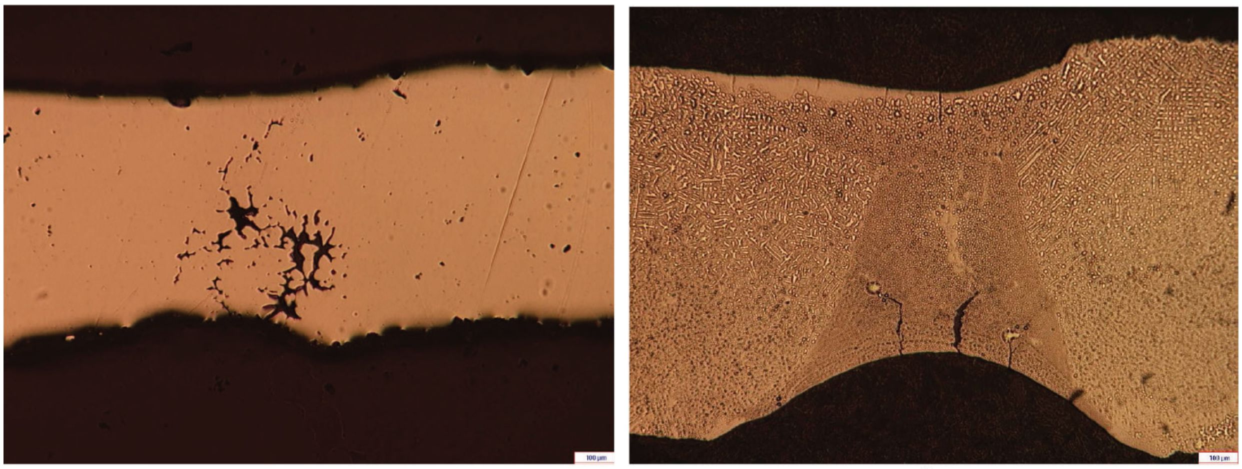


Figure 23. Microcracks in the BAA dendritic structure spread along the fragile compound precipitations, in case of fast cooling of the welded alloy.



a. b.

Figure 24. (a) Nonuniform dendritic structure with interdendritic cracks and microporosities. (b) Microstructural aspect of the welding cord in case of "C" alloy (Vaskut Kohàszati Kft), with cracks due to laser exposure, spreading from surface to center.

the crystalline grains with well-delimitated boundary limits, which are characteristic to the solidification process, appear in case of some welded joints (**Figures 23**, **24**, and **25**). This may often lead to alloy durification and fragile structure.

Metallographic analysis of the laser welded joints is shown in **Figures 26**, **27**, and **28**.

Figure 29 shows pellicular intergrain precipitations and spherical shape compounds, placed inside the crystalline grains.

Metallographic analysis indicates that welded CoCr alloys exhibit rather large microstructural defects, including interdendritic carbide precipitations, segregation, relatively large grains, and porosity, mainly in the BAA area. These microstructural defects may lead to crack initiation. The welded joints themselves (MA) show a rather good quality.

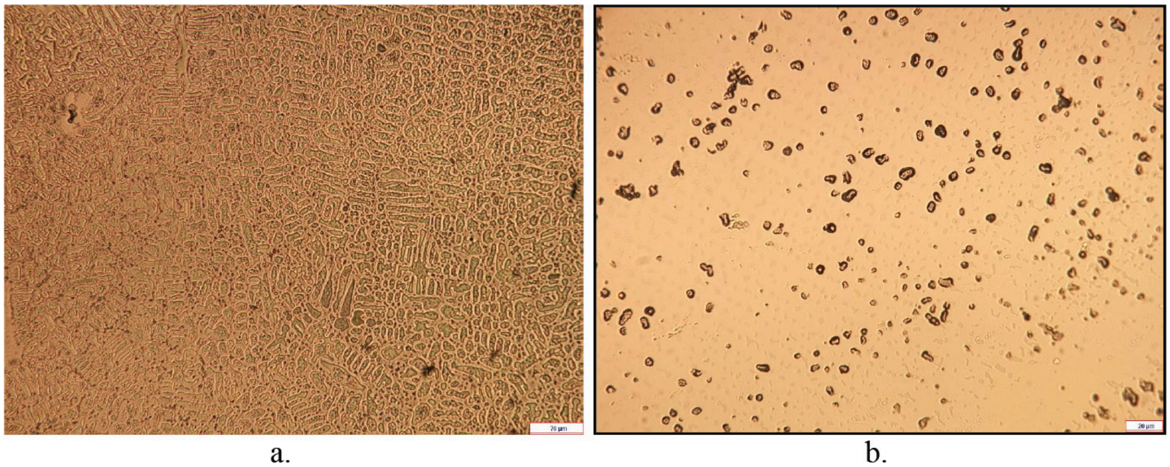


Figure 25. Wironit extra-hard (Bego) sample. (a) Welded on both sides, with nonuniform dendritic structure. (b) With thermal treatment, with nonuniform fine dendritic structure and carbide inclusions.

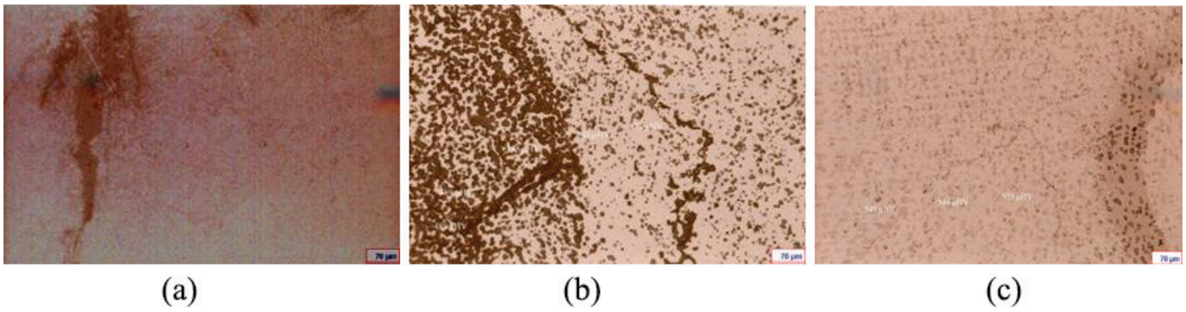


Figure 26. Microstructural aspect of Heraenium CE (Heraeus Kulzer). (a) Laser welded samples MA and TAA, microhardness values unchanged. (b) Laser welded samples without thermic treatment, MA microhardness values decreased up to 25%. (c) Micro pulse welded samples, heat treated, no microhardness changes in the TAA.

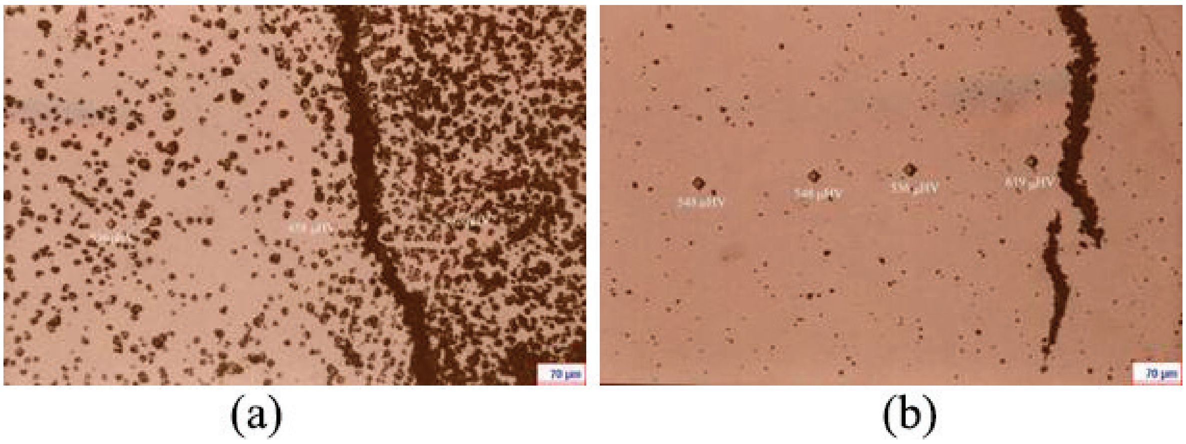
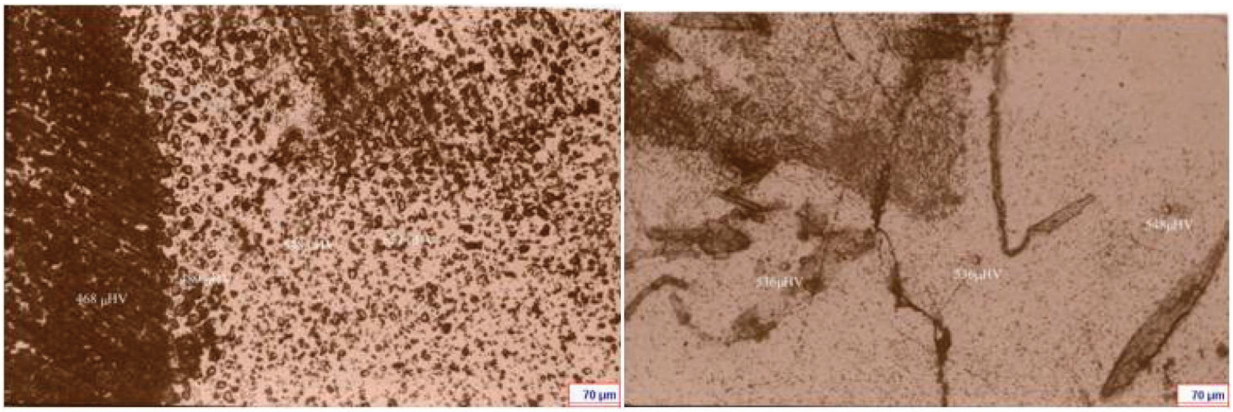


Figure 27. Microstructural aspect of Wironit extra-hard (Bego) laser welded samples. (a) TAA microhardness values lower up to 15%. (b) Samples with heat treatment, TAA microhardness values higher up to 16%.

Noninvasive analysis points out the structural defects of the three casted alloys, showing cracks which grow proportionally with the thickness of the alloy, within the BAA. These may be caused by casting, improper processing, and rapid cooling after welding [15, 16].



a. b.

Figure 28. Microstructural aspect of "C" alloy (Vaskut Kohàszati Kft) laser welded samples. (a) TAA microhardness values lower up to 30%. (b) TAA microhardness values unchanged.

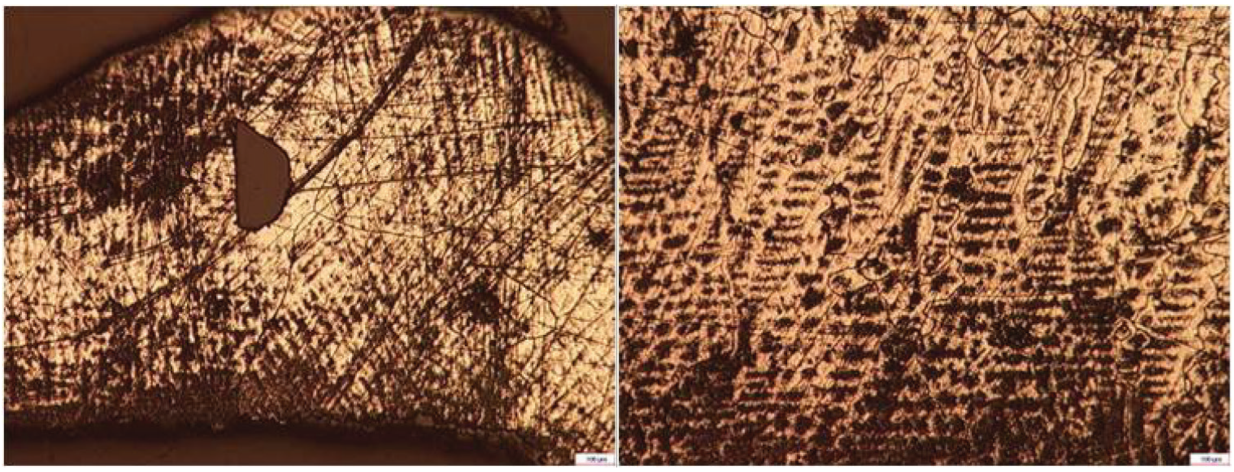
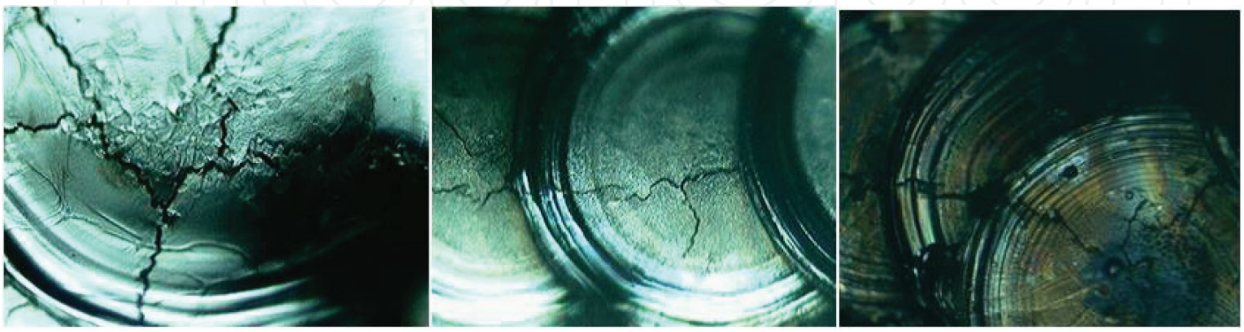


Figure 29. Metallographic aspects of pellicular intergrain precipitations, spherical shape compounds.



a. b. c.

Figure 30. Microscopic aspects of Wironit extra-hard (Bego) alloy for different laser beam sizes: (a) small, (b) medium, (c) large.

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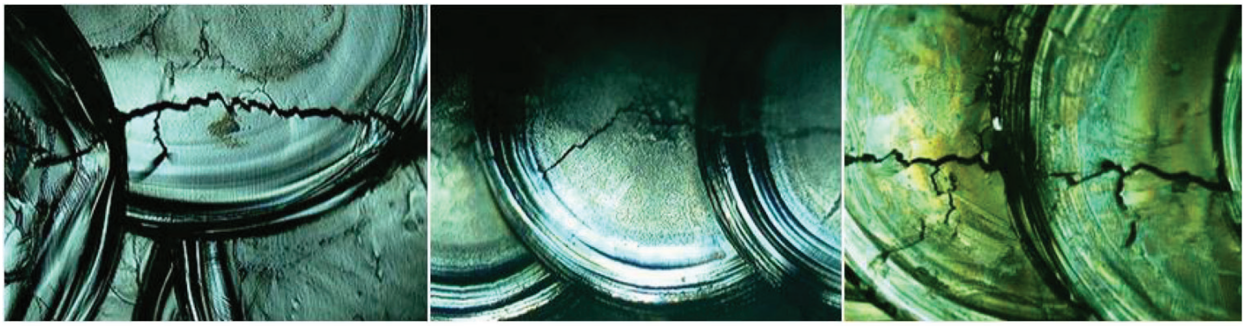


Figure 31. Microscopic aspects of "C" alloy (Vaskut Kohàszati Kft) for different laser beam sizes: (a) small, (b) medium, (c) large.

The welding defects (cracks) appear to be in connection with the laser beam size and laser power. Most of the cracks appear at big spot/ high power association, during the welding smoothing (**Figures 30** and **31**) [17].

4. Welding complex CoCrMoTi(Zr) alloys

Welding experiments on complex CoCrMoTi(Zr) alloys, CoCrMoZrTi alloy, CoCrMoTi4 alloy, and CoCrMoTi5.5 alloy [18–24], were performed by selecting three categories of parameters, a selection which was made following previous tests on cobalt alloys. For this purpose, the welding parameters were chosen, with three values of the laser spot power, namely, low power (1.9 W), average power (2.0 W), and higher power (2.3 W); the times of application of the spot, namely, short (1.1 s) or long (1.3 s); and the frequency of the spot application at two levels, respectively, 2.0 Hz and 3.0 Hz. (**Table 2**).

The macrostructural analysis carried out on the welded surfaces of the complex CoCrMoTi(Zr) alloys is shown in **Figures 32–34**. This analysis proved to be decisive in the selection of welding parameters as it allowed to highlight these parameters correlated with the macrostructural aspect. Thus, in the case of the first set of welding parameter values, all alloys presented similar macrostructural aspects, consisting of non-cracked welded cords. The second set of values resulted in partially satisfactory results, with all alloys presenting a nonconforming welded surface. Regarding the third set of welding values, it led to the most inappropriate results. Thus, in all alloys, the high value of the welding spot power generated the subsequent melting of the welding cord, due to the generation of sprays from the next step. It can be said that the welding performed with

Parameter	Power	Time	Frequency
Set 1	2.0 W	1.1 s	2.0 Hz
Set 2	1.9 W	1.3 s	3.0 Hz
Set 3	2.3 W	1.3 s	2.0 Hz

Table 2. Sets of parameters used for welding CoCrMoTi(Zr) alloys.

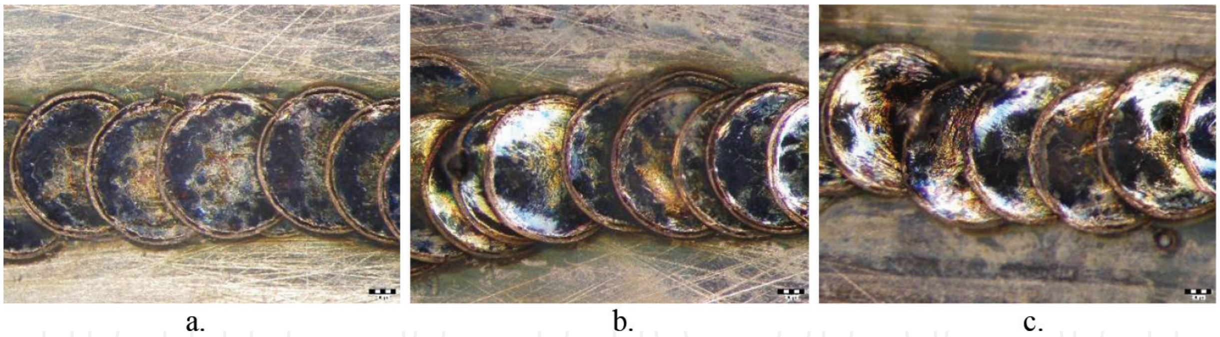


Figure 32. Macroscopic aspect of the welded CoCrMoZrTi alloy using different parameter values: (a) first set, (b) second set, (c) third set.

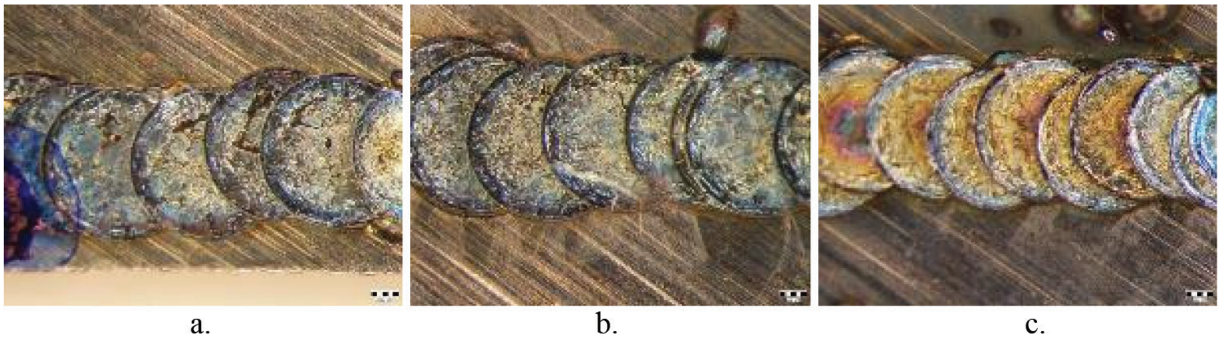


Figure 33. Macroscopic aspect of the welded CoCrMoTi4 alloy using different parameter values: (a) first set, (b) second set, (c) third set.

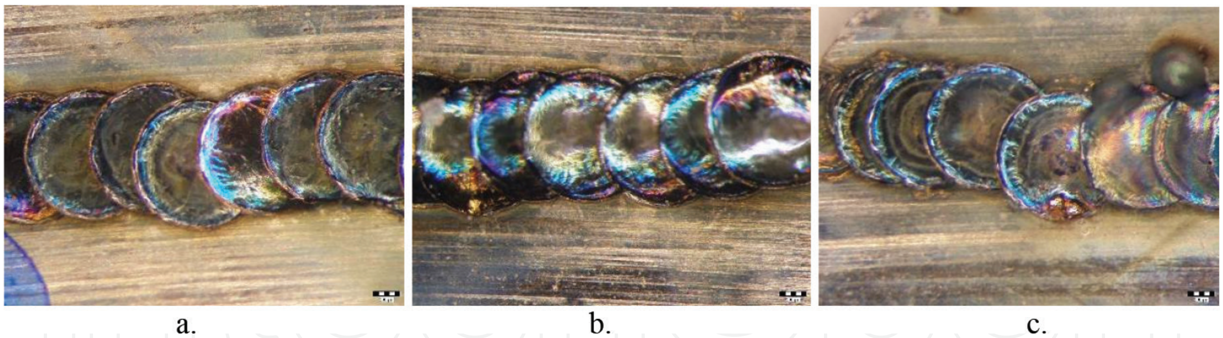
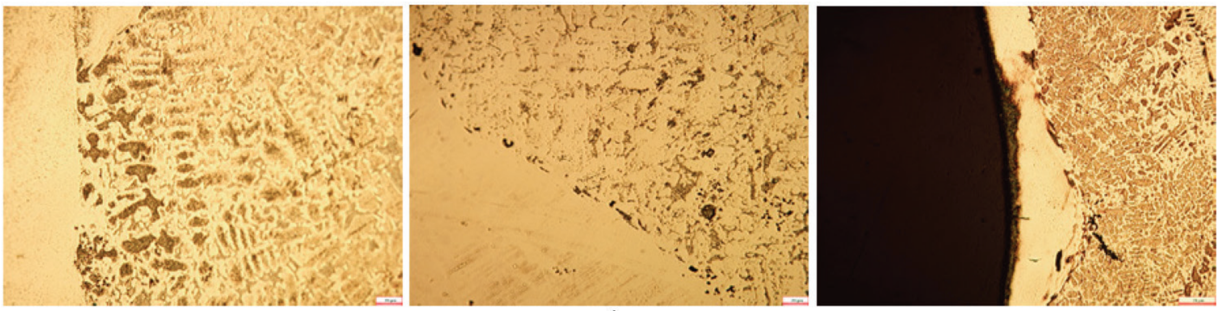


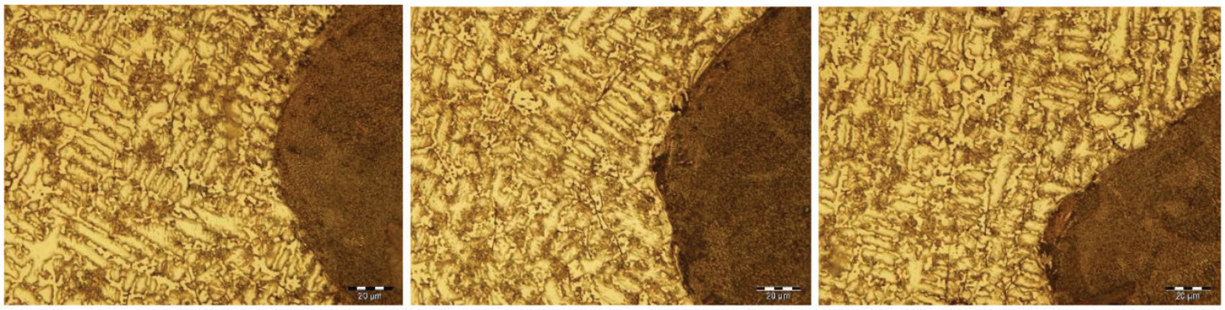
Figure 34. Macroscopic aspect of the welded CoCrMoT5.5 alloy using different parameter values: (a) first set, (b) second set, (c) third set.

the parameters corresponding to the first set of values generates the best quality welding cord, without the presence of cracks. The microstructural analysis (**Figures 35–37**) confirms the macrostructural one. In the case of the first set of welding parameters, no cracks were observed either in the welding cord or TAA in all alloys, irrespective of the thermal treatment state (**Figure 35a**, **36a**, and **37a**). In the case of the second set of values, the presence of cracks generated either on the welding cord and developed in the TAA (as for the CoCrMoZrTi alloy), or strong cracks in the center of the welding cord (CoCrMoTi4 alloy, CoCrMoTi5.5) are present. Similar observations were also recorded on



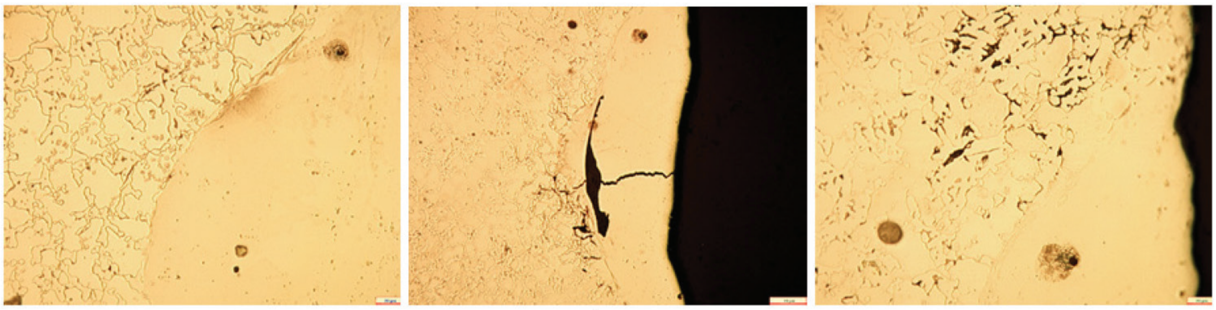
a. b. c.

Figure 35. Microscopic aspect of the welded CoCrMoZrTi alloy using different parameter values: (a) first set, (b) second set, (c) third set.



a. b. c.

Figure 36. Microscopic aspect of the welded CoCrMoTi4 alloy using different parameter values: (a) first set, (b) second set, (c) third set.



a. b. c.

Figure 37. Microscopic aspect of the welded CoCrMoT5.5 alloy using different parameter values: (a) first set, (b) second set, (c) third set.

samples welded using the third set of parameters, the difference being the dimensions and the crack propagation. Thus, in the case of the third set of welding parameters, larger cracks with transgranular propagation may be noticed in almost all situations.

5. Discussions

Laser and micro pulse welding is mainly used in dentistry for repairing damaged metallic parts of partial dentures or orthodontic appliances [25].

If welding is used for repairing or completing damaged areas of prosthetic pieces, structural modifications are expected, especially in TAA, regardless of the welding type. In this area, due to overheating and fast cooling, precipitates of certain alloy chemical compounds may appear. These precipitates increase the hardness of the welded metal and lead to fragile areas, which could crack during functional loads. Cracks may appear not only because of the mechanical stress to which the dentures are exposed but also during manufacturing stages and may lead to fracture. Thermal treatments improve the structure and quality of the casted and welded alloys [4].

In order to obtain dentures with good resistance, it is very important to assess the quality and potential structural defects of the welded parts.

The success of the welding procedure depends on the operator's dexterity and the choice of the welding parameters. Selecting the best combination of pulse energy, pulse duration, and peak power for each welding step is decisive [20, 24].

Laser welding is best suitable to weld titanium and its alloys because they have higher rates of laser beam absorption and lower thermal conductivity compared to other dental casting alloys such as gold or CoCr alloys; however, due to the strong reactivity of molten titanium with oxygen in ambient air, the incorporation of oxygen during laser welding may affect the joint strength.

The initial welding is carried out by using a small laser beam (which better penetrates the alloy); afterward, a large beam is used for surface smoothening. Optional welding may be carried out in argon protective environment. The pulsed mode is preferred.

In the case of base metal alloys, the beam diameter must not be smaller than 1.5 mm, a 0.8 mm depth being considered enough to obtain a good breaking resistance. In case of heavy loads, both sides of the defect are welded.

Welding without filler metal is very scrupulous and implies a perfect surface processing and a uniform proximity of maximum 0.1 mm (which enables a good welding resistance), which is difficult to obtain in daily practice. Furthermore, the penetration depth and the metallographic changes in the TAA are difficult to manage. From this point of view, welding with filler metal is better, because the breaking resistance is reproducible, welding being carried out by conducting heat along the interfaces.

Welded alloys without carbon act better than those which have carbon in their composition. During welding, excess carbide precipitations may occur, which leads to hardening (fragilization) of the TAA and possible cracks.

In case of repairs, an important element is determining the initial cause of the fracture. If it's the consequence of a casting or conception mistake, the welding will not last for long.

With a proper selection of laser parameters for welding, one may obtain very good welded pieces, with no cracks (as showed in our experiments carried on CoCrMoTi(Zr) system alloys).

6. Conclusions

The advantages of laser welding in dental laboratories may be summarized as follows: it is time-saving; potentially all types of metals may be joined, particularly titanium alloys; welds are made on the model, distortions being avoided; the absence of corrosion, because no soldering alloy is needed; good resistance of the welded area; and the possibility to weld in proximity of resins or ceramic materials without damage.

Compared to micro pulse welding, which needs the use of a changeable electrode, laser welding is superior, achieving the welding cord being faster and easier in case of laser welding.

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