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Intraoral welding of titanium dental implants: Characterization of the joints

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ABSTRACT

The aim of this work is to find the optimal conditions to obtain a continuous joint without alterations/oxidations in the intraoral welding of titanium by electric resistance technique. The proposed technique allows intraoral welding of titanium in order to obtain the solidarization of dental implants for improving their primary stability. Commercially pure titanium (c.p. Ti) wires and dental screws were welded by electric resistance technique. A metallographic and mechanical evaluation of the joining area was performed by electronic and optical microscopy, as well as by hardness measurements. The welding has been realized in different conditions by a circumferential pulse welding machine, in order to investigate the eventual drawbacks and to optimise the welding procedure. Moreover, the attention was focused on the use of a flux of argon during the procedure, in order to avoid oxidation and to improve the microstructural characteristics of the joint. The characterization of various welded Ti wires led to the individuation of the optimal conditions to obtain a continuous joint without alterations or oxidations. The best results were obtained by using two impulses and argon flux. A clinical case demonstrates the effectiveness of the technique in the improvement of dental implants primary stability.

1. Introduction

Titanium and its alloys are the metals of choice in biomedical applications due to their high biocompatibility, low density, good mechanical properties and corrosion resistance.

With the introduction of titanium by Tramonte in the early 1960s, it has been shown to implantologists the advantages of a material that, in addition to biocompatibility, allowed the opportunity to be welded and mechanically coupled in the mouth as reported by Hruska (1987). Due to the high diffusion of titanium based materials in dentistry, their weldability is a topic of interest in this field (e.g. orthodontic wires) as discussed by Matsunaga et al. (2015) for laser and electrical welding of various titanium-based wires, Iijima et al. (2008) for electrical resistance of β-titanium wires, Akman et al. (2009) for laser welding of Ti6Al4 V alloy and also by Wang and Welsch (1995) for tungsten inert gas and laser welding and infrared brazing of titanium. Weldability of commercially pure titanium (c.p. Ti) is in general very good. The main problems in the welding of titanium based materials are the formation of a heat affected zone and the high reactivity of titanium with oxygen, nitrogen and hydrogen at high temperatures as reported by Matsunaga et al. (2015) for laser and electrical welding of various titanium-based wires, Iijima et al. (2008) for electrical resistance of β-titanium wires, Akman et al. (2009) for laser welding of Ti6Al4 V alloy and also by Wang and Welsch (1995) for tungsten inert gas and laser welding and infrared brazing of titanium. Contamination of the weld metal and adjacent zone will increase tensile strength and hardness, but they reduce ductility to an unacceptably low value, such that cracks may occur even in conditions of only moderate restraint. The most likely contaminants are oxygen and nitrogen, picked up from the air, and hydrogen deriving from moisture or surface contamination. Li et al. (2005) suggested the maximum tolerable limits in weld metal as 0.3% oxygen, 0.15% nitrogen and 150 ppm hydrogen. Scrupulous cleanliness is essential for both parent metals, but in the case of intraoral welding, the use of medical grade and sterilized materials significantly reduces any inconvenience coming out from surface contaminants. Moreover, protective shielding with inert gases can be added as protection against oxidation, but Akman et al., 2009 underlined that it can lead to porosity in the final joint due to gas bubble entrapment, and its efficacy must be verified. The here proposed electric resistance

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welding is accomplished without filler metal, therefore, biocompatibility and corrosion resistance of the base metal can be retained. Mondani presented the first intraoral welder at the beginning of the 1980s (Mondani and Mondani, 1982) and it was based on electric resistance welding. The welding by electric resistance is a process in which the needed heat is locally provided by the electrical resistance of the material, under the flow of a high density current. Further studies allowed the author to design and patent, nationally (Lorenzon 0001396770, 2012a) and internationally (Lorenzon US 7 390 988 B2, 2008) a circumferential pulse welding machine. Kahraman (2007) indicated that,. for industrial application, Ti and its alloys are generally welded to each other by laser beam, electron beam and gas tungsten arc welding., Some others welding techniques, such as laser or plasma welding have been proposed for specific dental applications, as indicated by (Roggensack et al., 1993), but it is reported that they induce the presence of a heat affected zone, reducing the durability of the joints; it is larger in the case of plasma welding. Resistance welding is a useful method because it allows avoiding the presence of a heat affected zone (as here reported) and over-heating of the surrounding soft tissues. Moreover, Sundaresan et al. (1999) reported that the microstructure can be refined, by using quite short time of heating, without adversely affecting the intragranular microstructure. The technique described in the present paper is innovative because it allows the intraoral welding of titanium bars and dental screws in order to solidarize implants for an improvement of their primary stability with a peculiar process.

The main purpose of the joining of implants to a bar is to increase their primary stability, in order to finally promote the integration of implants with bone. Several screws implanted at the same time in the mouth, mechanically become a whole implant, because of the presence of the joined bar, which is able to distribute loads and stresses. Lorenzon (2012b) highlighted that joined implants structurally represent a completely different system from the individual unconnected implants. The most important element in mechanical coupling of the implants is the lack of the typical *peri*-cervical resorption. It is a direct consequence of the distribution of stresses on the intra-cortical cross section. As first, the welded bar improves the primary stability of post-operative retaining and then it transforms the structural system from simple to complex. The complex system (joined implants) can be described as a beam on several pillars, while the simple one (un-joined implants) consists of individual pillars. Lorenzon and Bignardi (2003) and Pierazzini (1979) evidenced that the biomechanical behaviour of the complex system is completely different, following well known laws of mechanics. The joining by an electro-welded bar leads to a long survival of complex prosthetic implants. The author has, in his clinical experience, several cases of implants surgically inserted since more than 25 years ago which are fully functional at the present time (Lorenzon 2007; http://www.centrochirurgicosrl.it/en/functional-implantology-dental-implants-clinical-cases/).

The author (Lorenzon 2007) clinically observed that if the bar is removed bone resorption occurs. This is not a harmless phenomenon, but it is a progressive alteration going on with the deepening of the lesion.

In this research work, a comparison between different welding conditions (one or two electric impulses, optional argon employment) has been carried out on some model junctions, realized between two titanium wires with an innovative welding resistance apparatus developed and patented by the author nationally (Lorenzon 0001396770, 2012a) and internationally (Lorenzon US 7 390 988 B2, 2008). The characterization has been performed by means of electronic and optical microscopy and hardness analyses. Moreover, an optimized junction between titanium wires of different diameters and titanium dental implants have been analysed. The best joint does not show the typical zone of oxidation associated with a heat affected interface described by (Hruska and Borelli, 1991). The creation of an un-oxidised circumferential ring is of relevance because it can result in protection from stress corrosion, due, for instance, to bacterial corrosion. Moreover, the structural integrity of the elements (implants and bar) is maintained, because of the absence of surface oxides. The band of thermally altered material, often observed on titanium after welding, is absent by using this technique.

2. Materials and methods

2.1. Samples preparation

The implants employed, as a model for this analysis, were commercial products manufactured by Functional Devices (FD t/s type). Titanium wires were made of commercially pure titanium (c.p. Ti) grade 2 (TITANMED) and cleaned by washing in water and alcohol before welding.

The equipment used for welding was a circumferential pulsing machine, it was designed by the author in order to avoid structural weakness of the intraoral joints (Lorenzon US 7 390 988 B2, 2008) and (Lorenzon 0001396770, 2012a). It is manufactured by Sintermedica (Sinter-1). The application of the electrodes to the elements to be welded was made by applying a pre-set pressure. The applied pressure allows a defined plastic deformation of the surfaces to be welded, transforming the joint contact from a point into an extended contact area. The surfaces are welded by the action of the current flow given by the first pulse (50–60 Hz). They reach a temperature that is equivalent to 70% of the melting temperature of titanium (data measured by a thermocouple). In this way, the joining is obtained in a very short time. The impulse application time must be strictly controlled because a short timeline is important to maintain the correct temperature at the interface. Then, a second current pulse is applied. It causes a heating at a temperature higher than alpha to beta transition (data measured by a thermocouple). A constant pressure and argon flux has been maintained (when it was used) until the cooling of the joint (ten seconds).

2.2. Joining characterization

As first, joining between two titanium wires (1.5 mm in diameter) was realised as a model for a preliminary analysis of the intraoral welding technique (wire–wire samples).

The effect of different welding parameters on the quality of the final joining was investigated. Four typologies of joining were studied, varying the number of applied electric impulses and the atmosphere during welding: one electric impulse without Argon flux (1 imp – AIR), one impulse with Argon flux (1 imp – Ar), two impulses without Argon flux (2 imp – AIR), two impulses with Argon flux (2 imp – Ar).

Samples were observed in sections in order to characterize the welded area.

Friction occurring during cutting of the sections could introduce artefacts on the joining area, so, in order to avoid them, the wires near the joining were carefully removed by grinding and polishing, till exposition of the section of the joining, as described by the authors in (Ferraris and Spriano 2010). The exposed section of the joining was mirror polished with abrasive papers (up to 4000 grid) for optical and electronic microscope observations.

Then surfaces were prepared for metallographic investigations: the samples were acid etched with Kroll solution, in order to highlight the microstructure in the welded zone as suggested by Iijima et al. (2008) and in the Struers technical note (Taylor and Weidmann, 2015) and then observed again by means of optical and electron microscopy.

The joining area was investigated by means of Scanning Electron Microscopy equipped with Energy Dispersive X-ray Spectroscopy for chemical analysis (SEM – FEI, QUANTA INSPECT 200, EDS – EDAX PV 9900), before and after acid etching.

The microstructure was investigated by optical microscopy (Reichert-Jung Me-F3) after surface acid etching.

The micro-hardness was evaluated on the wire and on the joining zone by means of a micro-indenter (Leitz Wetzlar Germany). At least 4 measurements per zone were performed. Data were represented as mean and standard deviation and were analysed by means of one-way ANOVA, with a significance level $p < 0.05$.

Furthermore, the joining between a titanium wire and dental screw was analysed (wire-screw samples), in order to simulate the intraoral welding of implants. 1.5 and 2 mm wires were considered and joined to commercially available dental implants. The welding was performed by using two electric impulses and Ar flux, because this condition was selected as the best performing at the end of the previously described characterization. Wire-screws samples were resin incorporated, grinded, polished and observed before and after metallographic etching, as previously described for wire–wire samples.

A clinical case is described, as an example. The patient was a 45 years old woman. She had removable dentures for 15 years. Then, a maxillary (on 7 implants) and mandibular (on 6 implants) dentures have been implanted, by using a transmucosal and flapless technique. The implants of each denture were welded to two titanium rods, by using the welding technique previously described.

3. Results and discussion

In electric resistance welding, the metal counterparts to be welded are positioned between the water-cooled electrodes, and then the heat is obtained by a large electrical current, in a short period of time (current pulse). There are three stages in the process. First the electrodes are brought together, against the metal parts and a constant pressure is applied. Next, the current is turned on and one or two current pulses occur. As last, there is a hold time in which the current is turned off and the pressure continued. The hold time forges the metal while it is cooling.

The macroscopic appearance of the analysed welded wires is reported in Fig. 1 (wire-wire) and Fig. 3 (wire-screw). An external dark blue area, in correspondence of the joining, can be observed for the sample prepared by using two electric impulses without Ar flux (Fig. 1 – sample called 2 imp – AIR). The dark blue colouration can be attributed to the oxidation of the outermost metal layer during the welding process and it is absent on the others samples. Li et al. (2005) reported few general rules usually considered for the evaluation of titanium welding. Under perfect gas shielding conditions, the weld will be bright and silvery in appearance. As contamination increases, the colour changes from silver to a light straw colour, then dark straw, dark blue, light blue, grey and finally a powdery white. The light and dark straw colours indicate a light contamination (normally acceptable). Dark blue indicates a heavier contamination, which may be acceptable depending on the service conditions. Light blue, grey and white indicate a high level of contamination (usually unacceptable).

The use of an argon flux does not allow oxidation, while without it a moderate oxidation occurs. The correlation between the weld surface colour and contamination is useful for a first evaluation of the joining, but it depends on several variables (the design of shielding devices, cooling rate). Moreover, the colour sequence repeats itself, as the oxidation thickness increases, so a detailed investigation of the cross sections of the samples must be performed in order to correctly evaluate the contamination/oxidation of the joining.

Fig. 1 reports SEM images of the cross sections of wire–wire joining. Each row of the figure deals with a different type of joining; the first column reports a back-scattered image of the joint at low magnification, detected before metallographic acid etching, while in the second column a secondary electrons image of an enlargement of the joining area, after metallographic acid etching, is reported. Back-scattered images can give information about the presence of chemical inhomogeneity, while secondary electrons images are related to the morphological appearance of the section. It can be observed that all the samples consist of welding extended on a large and constant area and they are not limited to a contact point. This is due to the application of a pre-set pressure before the current pulse, inducing a local constant plastic deformation of the elements to be welded and an enlargement of the contact area. Back scattering images show a homogeneous welding area, free from inclusions, porosities and chemical discontinuities or deeply oxidised areas, on all the samples. This result was confirmed also by the EDS chemical analyses (only titanium and a negligible amount of oxygen were detected both on the wire and on the joining area).

The secondary electron images, after metallographic etching, underline different features case by case. The presence of a series of micro-holes aligned along a discontinuity line (red circles in Fig. 1) is evident for samples prepared with a single impulse (both with and without Ar flux). This observation shows that one current impulse is not sufficient in order to get a continuous joint. On the other side, the sample prepared with two impulses, without Ar flux, shows an altered zone in correspondence of the welding area (red circle on the image, Fig. 1). This observation evidences that welding must be realized under an inert atmosphere, because of the high reactivity of titanium, leading to oxidation, not only on the outermost layer but also within the welded section. Titanium is a reactive metal; oxygen and nitrogen will diffuse into titanium at temperatures above 400 °C, raising the tensile strength, but embrittling the metal. As last, the sample prepared with two impulses and Ar flux results completely homogeneous, without discontinuities or pores, as well as altered/oxidised areas in the joined cross area.

Fig. 2 reports the optical microscope observation of the joining after metallographic etching.

Low magnification images (first column) underline a reduction in crystalline grain-size in the joining area, which can be attributed to the rapid cooling of the metal after welding. The second column of Fig. 2 collects higher magnification images of the joining area. These observations confirm the SEM analyses (Fig. 1), in fact a discontinuity line can be detected on the samples prepared with a single impulse (both with and without Ar flux) and a dark zone can be noted in correspondence of the welding line (comparable with the altered zone observed at SEM) on the sample prepared with two impulses without Ar flux. On the other hand, a completely homogeneous welding can be observed on the joining prepared with two electric impulses under Ar flux.

It can be concluded that both the application of two electric impulses and of an inert gas (Argon) flux are needed in order to obtain a continuous and not altered welding. The obtained result is of interest because of the absence of a heat affected zone, porosity and grain growth, as reported for joining realized by plasma or laser welding by Matsunaga et al. (2015) for laser and electrical welding of various titanium-based wires, Iijima et al. (2008) for electrical resistance of β-titanium wires, Akman et al. (2009) for laser welding of Ti6Al4 V alloy, Wang and Welsch (1995) for tungsten inert gas and laser welding and infrared brazing of titanium and Roggensack et al. (1993) for laser- and plasma-welded titanium. It is reported that a reduction of durability is related to these effects. The time requested for the heating and cooling of the welding is critical at this purpose; Roggensack et al. (1993) reported that plasma welding requires a long and continuous process, inducing the presence of a large heat affected zone and grain growth.

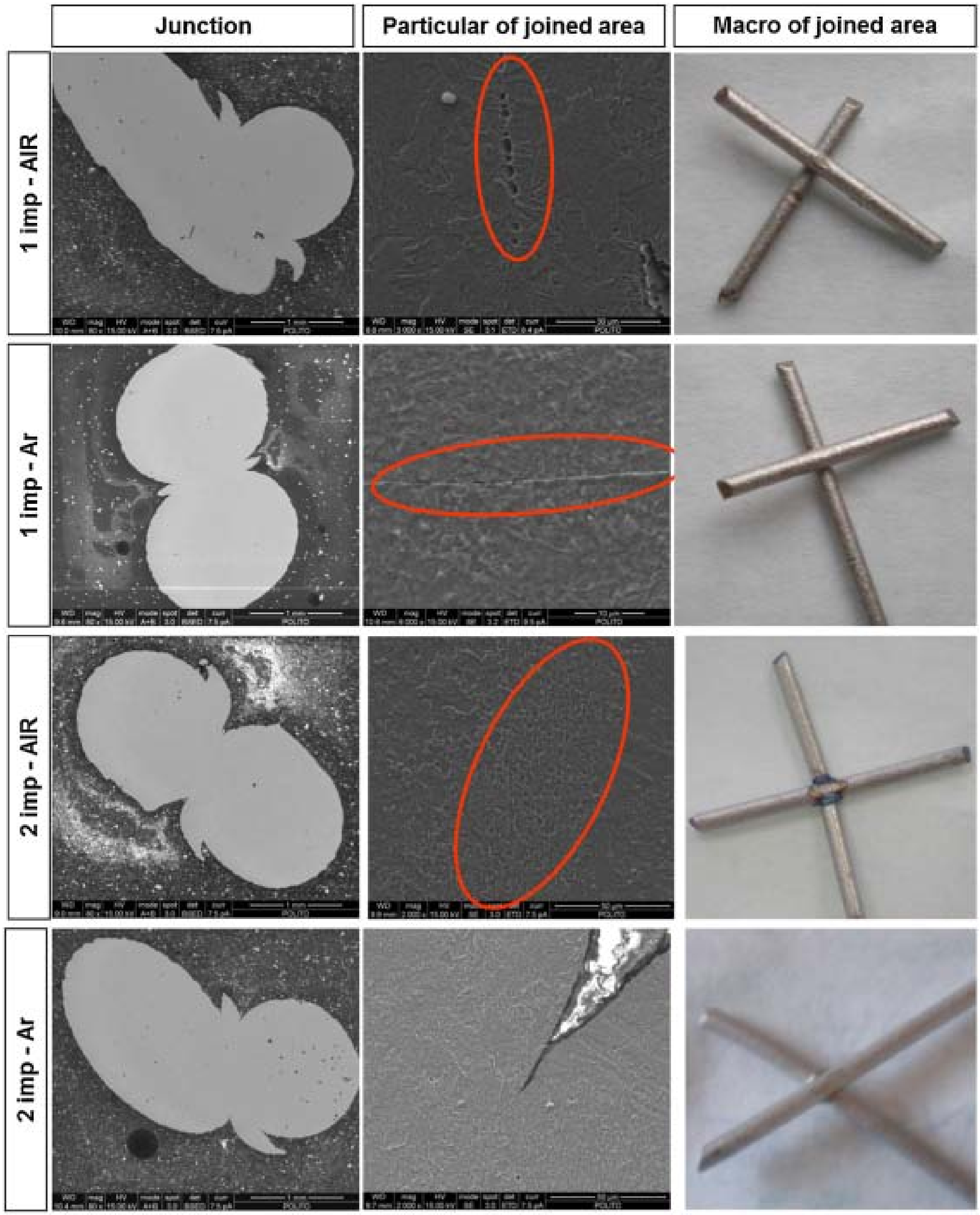

Fig. 1. SEM and macro observations of wire–wire junctions: 1 impulse without Ar employment (1 imp – AIR, first row), 1 impulse with Ar employment (1 imp – Ar, second row), 2 impulses without Ar employment (2 imp – AIR, third row) and 2 impulses with Ar employment (2 imp – Ar, last row).

The mean values of Vickers micro-hardness (inside and outside the joining area), are reported in Table 1.

Table 1
Micro-hardness values of samples analysed both inside (JOINING) and outside the joining area (WIRE).

	HV – Micro-Hardness			
	WIRE		JUNCTION	
	Mean	StDev	Mean	StDev
1 Imp-AIR	204.75	17.29	205.25	15.39
1 Imp-Ar	218.00	9.85	213.75	17.46
2 Imp-AIR	233.60	29.77	224.76	11.94
2 Imp-Ar	212.52	13.22	193.87	7.58

The difference between the hardness of the wire and the joining area is not statistically significant ($p > 0.05$) for any of the considered samples. So, it can be concluded that the proposed welding technique does not alter metal hardness inside the joining. This is of relevance because a too high hardness in the joining area could result in a fragile fracture, while a low hardness could be due to insufficient adhesion between the two elements. On the other hand Akman et al. (2009) reported a significant increase of the hardness in the joining area for laser welded titanium. The same problem has been evidenced by Wang and Welsch (1995) for tungsten inert gas welding and infrared brazing of titanium based materials. by. The use of a gas shielded process (argon flux during welding) is essential in order to avoid embrittlement, due to the oxygen and nitrogen diffusion within the joined cross area. No bubbles or

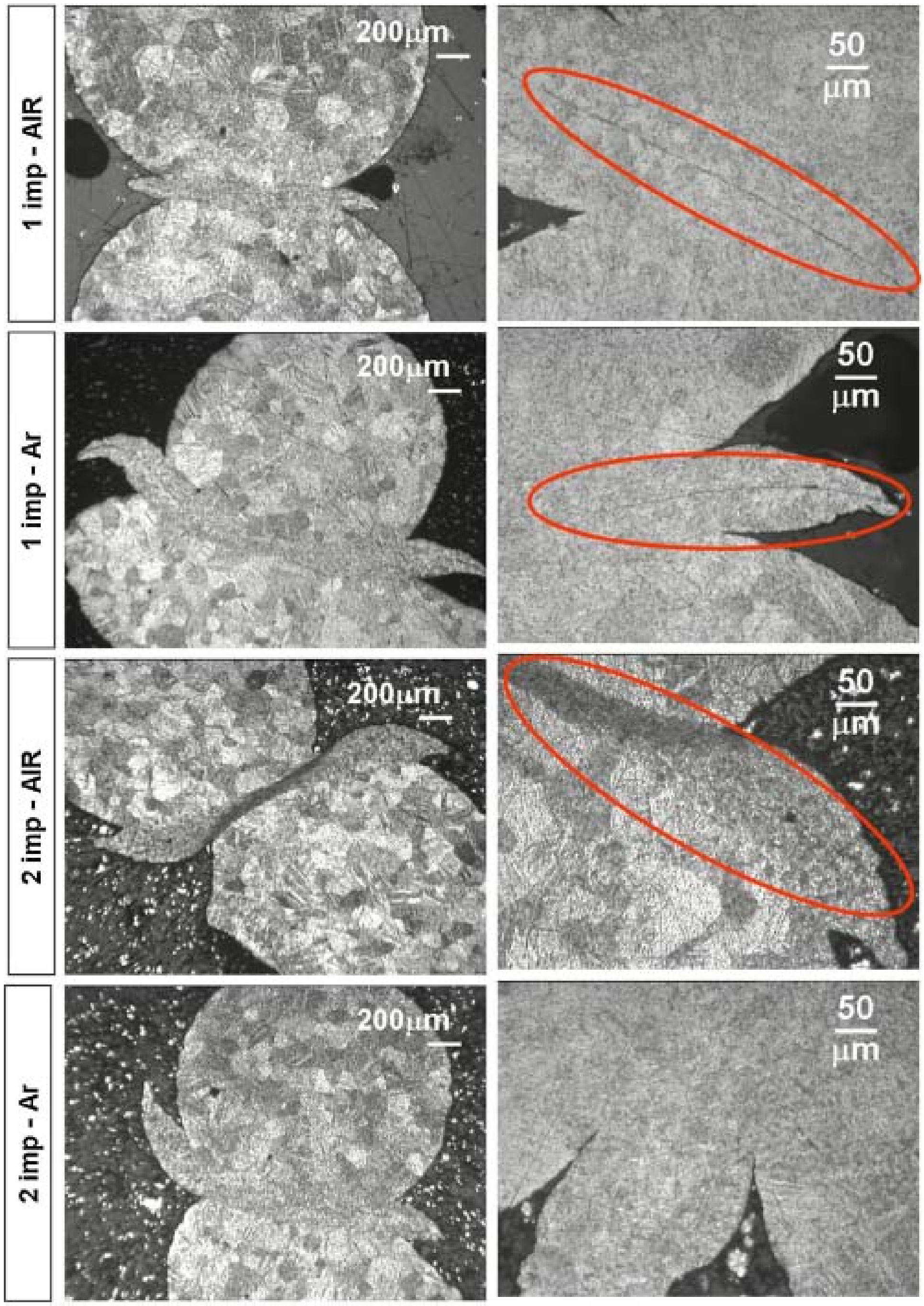

Fig. 2. Optical microscope observations of wire–wire junctions: 1 impulse without Ar flux (1 imp – AIR, first row), 1 impulse with Ar flux (1 imp – Ar, second row), 2 impulses without Ar flux (2 imp – AIR, third row) and 2 impulses with Ar flux (2 imp – Ar, last row).

porosity have been detected in the samples prepared with argon flux in the present research work. This is due to a careful control of the process parameters and it is of interest because porosity free joints can maintain mechanical properties of the staring material.

Optical and macro observation of the wire-screw samples (2 current pulses – Ar flux) are reported in Fig. 3. A sky blue coloration is present on a small area around the welding, even if Ar flux has been used. It can be explained considering the different diameter of one element of the joining (the implant) respect to the wire used in the previous samples. So, it must be taken into account that the efficiency of the Argon flux in order to guarantee an inert atmosphere during welding, is lower if the dimension of the elements to be welded increases.

Optical images of the joining after metallographic etching evidence a different microstructure between the wire and the implant, which is due to their different manufacturing process. A refined microstructure is shown on the welding zone, due to its rapid cooling down, as previously reported for wire–wire joining.

The joining appears uniform, without any discontinuity line, altered zone or porosity for both the types of samples. The presence of an external blue coloration is limited to the outer surface of the welded elements so it does not influence the welding characteristics. These features result independent from the applied power during welding, several joining between 1.5 mm wires and screws, prepared with different powers (the current is 320 A at the highest power) were analysed, obtaining the same results (data not shown).

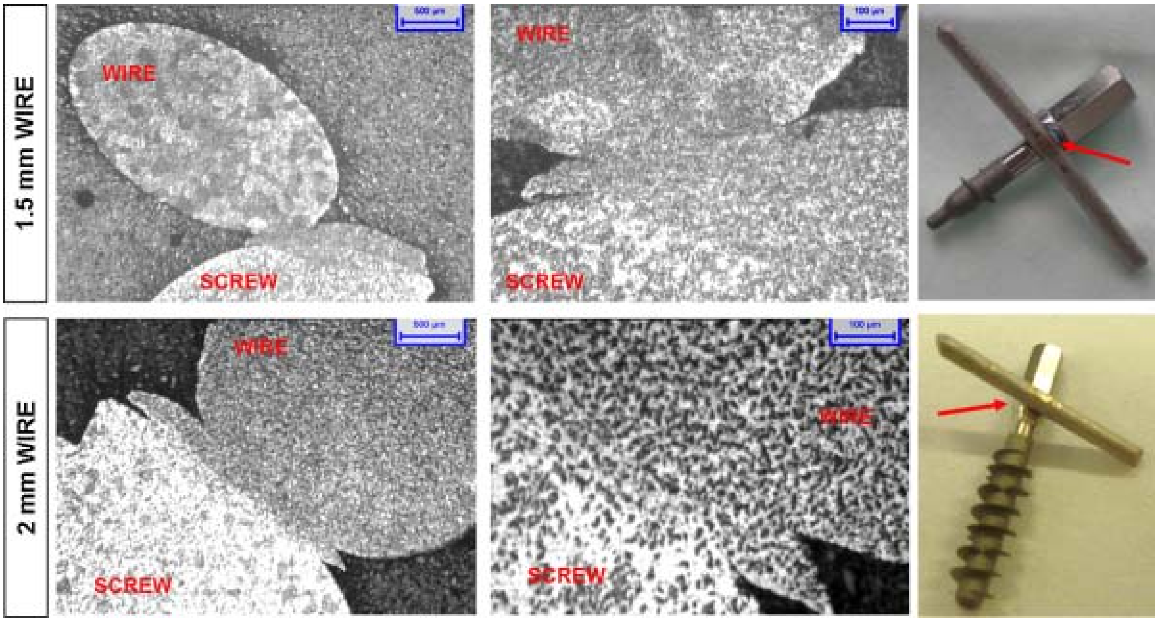

Fig. 3. Optical and macro observation of wire-screw joining (1.5 and 2 mm wires, respectively first and second rows) after metallographic etching.

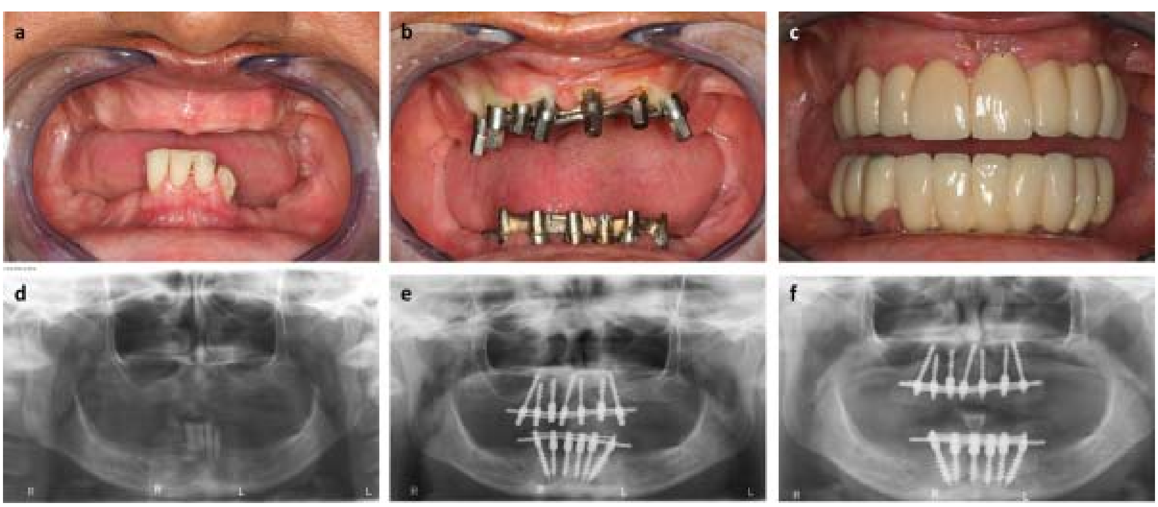

Fig. 4. Clinical case pre-surgery image (a) and RX (d), post-surgery image (b) and RX (e), 5-year follow up image (c) and RX (f).

It must be underlined that, during the application of the electrical impulses and the heating of the titanium parts, no heating occurs on the soft tissues around the joining area, by using the described equipment, because heat is dissipated by the copper electrodes (the thermal conductivity of copper is about 20 times as titanium is). Another important point is that the use of weak or deformable clamps must be avoided, because it may cause side effects, such as sparks from the electrical arc, which can increase the temperature around the joints (overheating of intra/peri-oral tissues).

It is important to maintain a constant pre-set pressure of the electrodes, in order to get a constant contact area of the joint; it is given by a calibrated spring preload. By using it, the applied pressure is not dependent from the operator's hand and it is strictly constant. The importance of protection by an argon flux is highlighted because it eliminates the so-called "heat affected zone" that leads to the degradation of the mechanical strength of the joint.

As an example, a clinical case is here reported and described. The preoperative situation (Fig. 4) showed atrophy of the distal areas of the jaws and the teeth had an inverted ratio of crown/root (from 2/3 to 1/3). A maxillary (on 7 implants) and mandibular (on 6 implants) dentures were implanted, by using a transmucosal and flapless technique. The implants of each denture were welded to two titanium rods, by using the welding technique previously described.

The images of the post-operative situation (Fig. 4b and e) are reported, as an example, in order to better describe the type of implant which can be realized, by using the technique of intraoral welding above described. The radiograph control at five years (Fig. 4c and f) revealed the absence of a cone of *peri*-cervical resorption. This effect is related to the decrement of the stress state, due to the presence of the welded rods, at the intra-cortical passage section.

4. Conclusions

Different types of joints, prepared with an innovative intraoral welding method, have been characterized. The use of a pre-set pressure, on the electrodes, allows a large and constant contact area, instead of a point joint. No inclusions, porosity or compositional alterations have been detected inside the joining area. The employment of a single electric impulse, during welding, leads to the formation of a discontinuity line, constituted of aligned micrometric holes, while the introduction of a second impulse favours the development of a continuous joining. Welding performed by using two impulses and without Ar flux induces the formation of an altered zone, in correspondence of the joining. The combination of Ar flux and two electric impulses allows a continuous and uniform welding. The hardness is not altered though the joint area and it guaranties good mechanical resistance.

This technique allows a uniform and continuous joining, both between Ti wires of different diameters (1.5 and 2 mm) and between wires and an oral implant.

Conflict of interest

Authors have no conflict of interest.

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