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# Comparison between traditional and alternative biocompatible welding techniques used in orthodontic devices

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## Abstract

**Objective:** To compare the mechanical strength of joints made by conventional soldering with those made by alternative, more biocompatible, methods (spot, tungsten inert gas [TIG] and laser welding), and to compare the microstructural morphology of wires welded with these techniques.

**Design:** In vitro, laboratory study.

**Methods:** Forty stainless-steel wire segments with 0.8-mm diameter were joined by silver soldering, spot, laser and TIG welding. Ten specimens were produced for each one. Tensile strength test was performed 24 h after welding on the Emic DL2000™ universal testing machine, using a load cell of 1000 N with a crosshead speed of 10 mm/min.

**Results:** The highest tensile strength mean values were obtained with silver soldering (532 N), next were laser (420 N), spot (301 N) and TIG (296 N) welding. Statistically significant differences were observed between the groups; the Dunn post-hoc test revealed differences between laser and spot welding ($p$=0.046), laser and TIG ($p$ = 0.016), spot and silver ($p$ <0.001), and silver and TIG ($p$ <0.001).

**Conclusion:** Laser welding strength is high, and comparable to silver welding. Spot and TIG techniques present comparable and significantly lower strengths. The four methods presented resistance values compatible with orthodontic use. The microstructural morphology is different for each technique. The association between the mechanical performance and the microstructure evaluation shows that laser presented the highest quality joint.

## Keywords

welding, orthodontics, dental soldering, biocompatibility

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## Introduction

Orthodontic treatment often requires welded appliances, such as lingual arches and maxillary expanders. Adequate strength of these devices is mandatory, as breakages may delay treatment time, damage tissues, or cause aspiration and swallowing (Bock et al., 2009). These appliances are often made with silver soldering, a conventional method that is highly operator dependent and uses Silver (Ag) brazing alloy to join other metals (Hurt, 2002; Ntasi et al., 2019). Excessive wire heating during this process may lead to oxidation, joint failure and low mechanical strength of the appliances (ISO 9333:2006; Ntasi et al., 2014; Perveen at al., 2018). Besides these limitations, these joints are prone to galvanic corrosion due to the soldered Ag alloy (Jacoby et al., 2017; Ntasi et al.,

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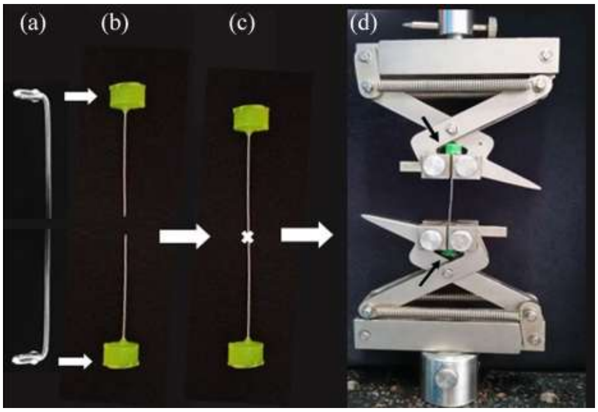


**Figure 1.** Test specimen preparation and positioning for the tensile strength test: (a) retention bend; (b) insertion in acrylic resin; (c) soldering; (d) specimens on the testing machine.

2019; Perveen et al., 2018; Muguruma et al., 2018). Niquel, Zinc, Cupper and Cromium may dissolve in the oral cavity and cause adverse biological effects (Freitas et al., 2009; Jacoby et al., 2017; Ntasi et al., 2014, 2019; Perveen et al., 2018; Schacher and De Menezes 2020; Sestini et al., 2006). Also, Ag nanoparticles have been ranked as strongly cytotoxic (Pellissari et al., 2020) and may affect cognitive, sensory and motor functions, which can result in brain and liver damage (Chen et al., 2016). The possibility of using different welding methods to overcome this lack of biocompatibility is of great interest to orthodontists. Alloy-free methods such as spot, tungsten inert gas (TIG) (Bock et al., 2009; Fornaini et al., 2009; Rocha et al., 2006; Wang and Welsch, 1995), a well-known gas tungsten arc welding and laser welding are alternatives (Bock et al., 2008b; Nascimento et al., 2012; Muguruma et al., 2018). Laser increased its application in the orthodontic field (Nalcaci and Gokakoglu, 2013) and may also be used for welding.

Spot welding presents higher biocompatibility (Nascimento et al., 2012; Sestini et al., 2006) but the mechanical strength may vary according to wire and joint configuration (Nascimento et al., 2012). TIG welding and laser welding present no galvanic corrosion, small focus and argon coating that prevents oxidation around the joint (Heidemann et al., 2002; Sestini et al., 2006; Solmi et al., 2004; Perveen et al., 2018; Muguruma et al., 2018). These two methods offer high biocompatibility and may present adequate mechanical strength, and are therefore advantageous to orthodontics (Perveen et al., 2018; Muguruma et al., 2018; Wang and Welsch, 1995). However, few studies compare these techniques for orthodontics, and their methodological differences hamper comparison between the results (Bock et al., 2008b; Muguruma et al., 2018; Wang and Welsch, 1995).

Considering the biological risk of silver soldering and the possibility of replacing it with alternative methods, the aim of the present study was to compare the mechanical strength of joints made by the conventional brazing method with those made by welding techniques that do not use filler metal. In addition, our purpose was to compare the microstructural morphology of welded stainless-steel orthodontic wires made by silver soldering, spot welding, TIG welding and laser welding to better understand the welding processes currently available for orthodontics.

## Methods

### *Welded joint*

A pilot study was conducted to calculate the sample size. Five welded stainless-steel wires were generated for each technique: silver, spot, TIG and laser welding (n = 20). The samples were submitted to tensile strength test. The largest mean difference between groups (212.01 N) and the largest standard deviation (100.784 N) were applied. A power of 80% and significance level of 5% were considered. Minitab Inc.® 17.1.0 (State College, PA, USA) was used to calculate sample size. The result showed a minimum of 06 specimens per group, with a total sample of 24.

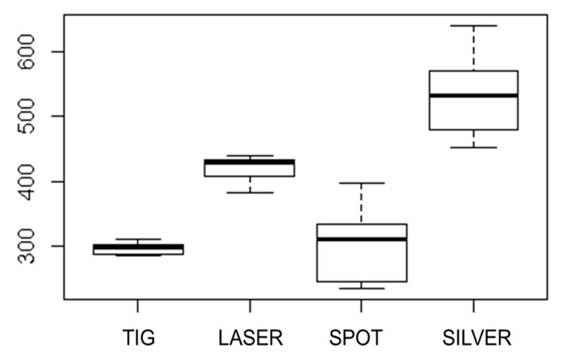
Round 0.8-mm stainless-steel wires were cut into 50-mm segments. For each joining method, 10 specimens were made (n = 40) to overcome any eventual loss due to failure. The total sample was divided in 4 groups: Group 1 (TIG welding), Group 2 (laser welding), Group 3 (spot welding) and Group 4 (silver welding). Representative samples of each joining method were produced for microstructure evaluation.

Test specimens were made for proper fit of the wires on the universal testing machine. For retention, a 10-mm round bend was made at the end of each segment followed by a 90º bend with a bird beak plier (Orthopli, Philadelphia, PA, USA). The retention ends were inserted in the center of a silicone matrix (®) of 10-mm diameter and 5-mm height, with the aid of utility wax. Self-cured acrylic resin (Vipi, Pirassununga, Brazil) was poured inside this structure. After the curing process, all wires were fixed to the matrix base (Figure 1).

The free ends of the wires were prepared in a standardised manner with low-speed silicon carbide stones. Silver and spot welding were performed by the same operator, and TIG and laser techniques were performed in specific laboratories by the same operator.

Silver welding used 50 mm of silver solder alloy and 10 mg of flux (Morelli® Sorocaba / SP, Brazil). The test specimens were immobilised with Matthieu clamps (Orthopli®) at a distance of 0.3 mm between the segments. Flux was applied to both ends of the wires. A dental soldering torch with butane gas (Blaser®) and flame of approximately 10 mm was used. Welding used the apex of the flame, at the reducing zone. Silver solder was added and heated until it flowed around the wires. After soldering, the assembly was immediately removed from the flame and cooled at room temperature.

**Figure 2.** Box plots showing tensile strength values (N).



Spot welding was performed with an overlap of 5 mm between the wires and two welding points. The machine (SMP 3000, Kernit, Indaiatuba, Sao Paulo, Brazil) was set at 30 W for 1 ms, and the ends of the electrodes were flattened with 400 mesh sandpaper before welding.

Laser and TIG welding followed the manufacturer's instructions. Laser (Sisma® LM-D60, Piovene Rocchette, Italy) was set with a power of 11% and speed of 6.5 Hz. The beam diameter was 0.6 mm. TIG welding (Lampert ® Puk D2, Werktechnik, GmbH) was performed with a power of 30% and speed of 15 ms.

All welded joints were polished with gray stone for 20 s, followed by silicone rubbers in the following sequence: white for 15 s (L22 polishing rubber, EVE, Pforzheim, Germany); brown for 30 s; and green for 30 s (EVEFLEX HP 708 and 808, EVE, Pforzheim, Germany).

### Morphology and microstructure evaluation

The wires were initially embedded in PVC rings using oven-cured epoxy resin at 60 °C for 24 h, to fix the sample and facilitate metallographic preparation. Specimen preparation is an important part of the process as it ensures correct observation of internal structures. Samples were initially prepared with a sequence of #220, #320, #400, #600 and #1200 mesh abrasive papers with rotating discs under constant water irrigation. Then they were polished with 1.0-µm alumina particles in a Pantec Polipan-Ud® polishing machine and 0.30-µm particles in a 300-rpm rotation Struers DPU® polishing machine. Fry's reactive agent was used for 5 s (90 g of $CuCl_2$, 120 mL of $H_2O$: HCl and 100 mL of distilled water). The piece was then removed and washed in distilled water. Micrographs were generated by an Olympus PMG3 optical microscope (50× and 100× magnification) with an EDN-2 reading program.

The morphology analysis was carried out through scanning electron microscopy (FEG Inspect F50 – FEI®) using secondary (SE) and back-scattered electron (BSE) detectors. The BSE images are generated by a contrast mechanism between different atomic numbers of the elements present in the material. SE imaging responds minimally to atomic number variations, providing insight into the material's topography and not on its chemical composition.

The samples were metallised with gold (Q 150 R ES, Quorum, UK) and observed at magnifications of 50×, 100×, 200× and 500×. The parameters used were voltage of 20 kV and point resolution of 1.2 nm.

### Welded joint resistance test

Tensile strength test was carried out in a universal testing machine (EMIC DL-2000). All samples were stretched with the same load until breaking point. After the test, the wires were analysed to determine the rupture site using an optical microscope under 10× magnification.

### Statistical analysis

Data were analysed for normal distribution using the Shapiro–Wilk test. Despite normal distribution, the analyses of variance (ANOVA) identified differences between groups, violating a one-way ANOVA assumption. Thus, we started with the non-parametric alternative of Kruskal–Wallis. The effect size of this test was calculated as the Eta-squared, based on the H-statistic: eta2[H] = (H - k + 1)/(n - k); where H is the value obtained in the Kruskal-Wallis test; k is the number of groups; n is the total number of observations. According to the literature, we considered a small effect from 0.01 to 0.06, moderate effect from 0.06 to 0.14 and large effect higher than 0.14. Dunn's post-hoc test with Bonferroni correction was used. All tests considered a significance level of 95% with p-value less than 0.05. The software used was R version 4.0.2 (R Core Team, 2020).

## Results

Statistically significant differences were found between groups ($P < 0.001$, Kruskal–Wallis test). Differences occurred between groups 2 and 3 ($p = 0.046$), 1 and 2 ($p = 0.016$), 3 and 4 ($p < 0.001$), and 4 and 1 ($p < 0.001$) (Dunn's post-hoc test). There were no significant differences between 2 and 4 and between 3 and 1 ($p > 0.05$). (Figure 2) The effect size of the Kruskal-wallis test was small in all groups (0.01).

**Table 1.** Mean tensile strength values (N).

| Group | Welding technique | n | Mean ± SD |
|---|---|---|---|
| 1 | TIG | 10 | 296 ± 8 |
| 2 | Laser | 10 | 420 ± 18 |
| 3 | Spot | 10 | 301 ± 54 |
| 4 | Silver | 10 | 532 ± 61 |

**Figure 3.** Silver joint. (a, b) Back-scattered electron images with magnifications of 50× and 100×. (c) Secondary electron image with 100× magnification. (d–g) Metallography with 50× and 100× magnification. Porosities are indicated by the arrows. Micromechanical union can be observed, with coverage of the wires by the Ag alloy.

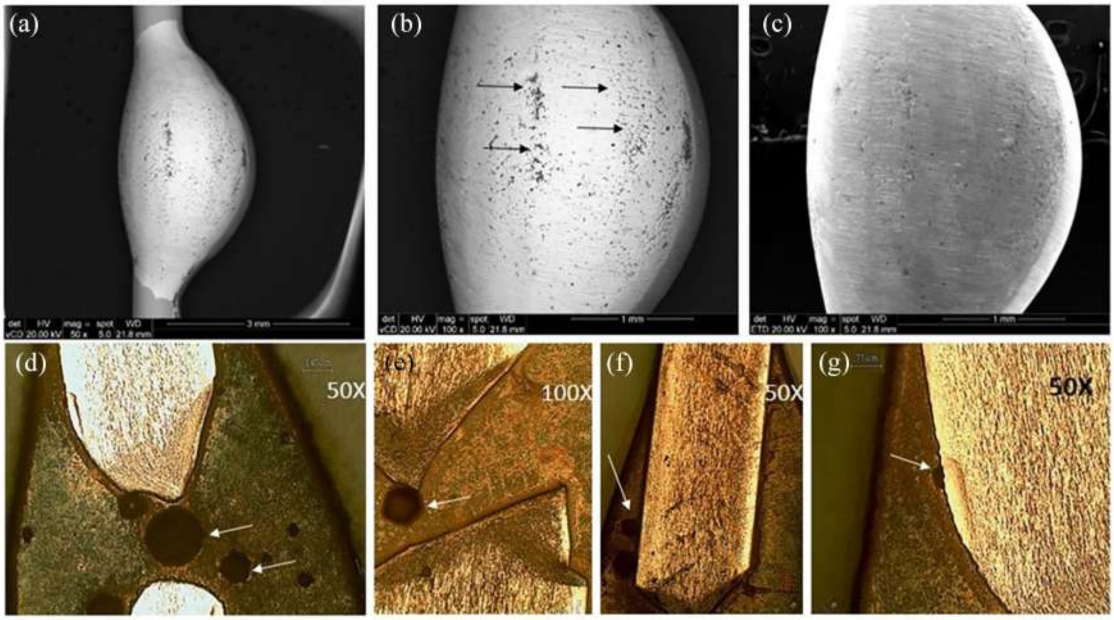


**Figure 4.** Spot joint. (a) BSE image with 100× magnification, (b) secondary electron image with 100× magnification, (c) BSE image of point 1 with 500× magnification, (d) BSE image of point 2 with 500× magnification, (e) metallography of point 1 with 50× magnification, (f) metallography of point 2 with 50× magnification. The distinct point configurations can be observed. (e, f) The arrows indicate (e) lack of union between the segments in a deeper layer and (f) the heat-affected zones. BSE, back-scattered electron.

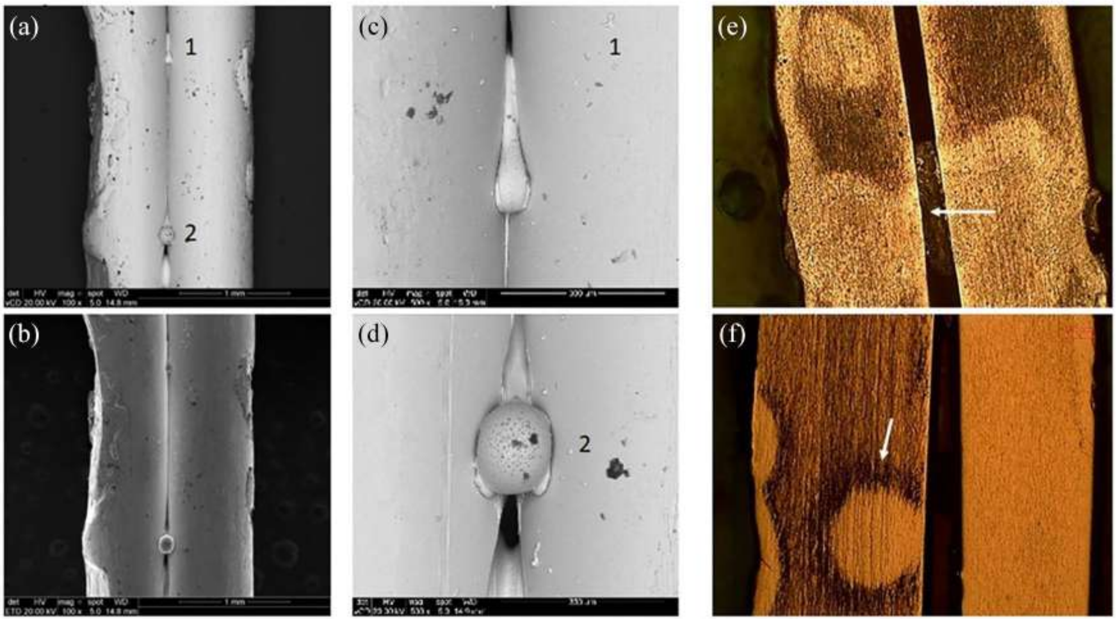


**Figure 5.** Tungsten inert gas joint. (a, b) BSE images with 100× and 200× magnifications, (c) secondary electron image with 200× magnification, (d) BSE image of point 1 with 500× magnification, (d) BSE image of point 2 with 500× magnification, (e) metallography with 50× magnification, (f) metallography with 100× magnification. The arrows in (e) indicate the large heat-affected zone. In (f), cracks may be observed. BSE, back-scattered electron

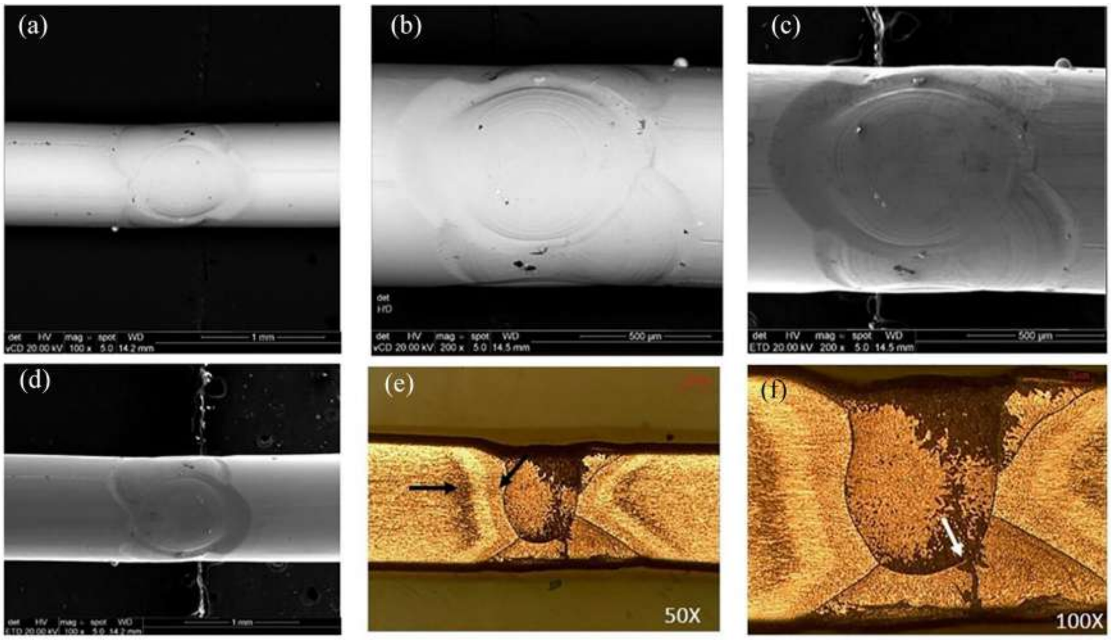


**Figure 6.** Laser joint. (a, b) Back-scattered electron images with 100× and 200× magnifications, (c) secondary electron image with 200× magnification. The arrows point to adequate union between the segments. The regions indicated by the asterisks are compatible with chromium oxide formation. (d–f) Metallography with 50× and 100× magnification. The arrows point to the small heat-affected zones.

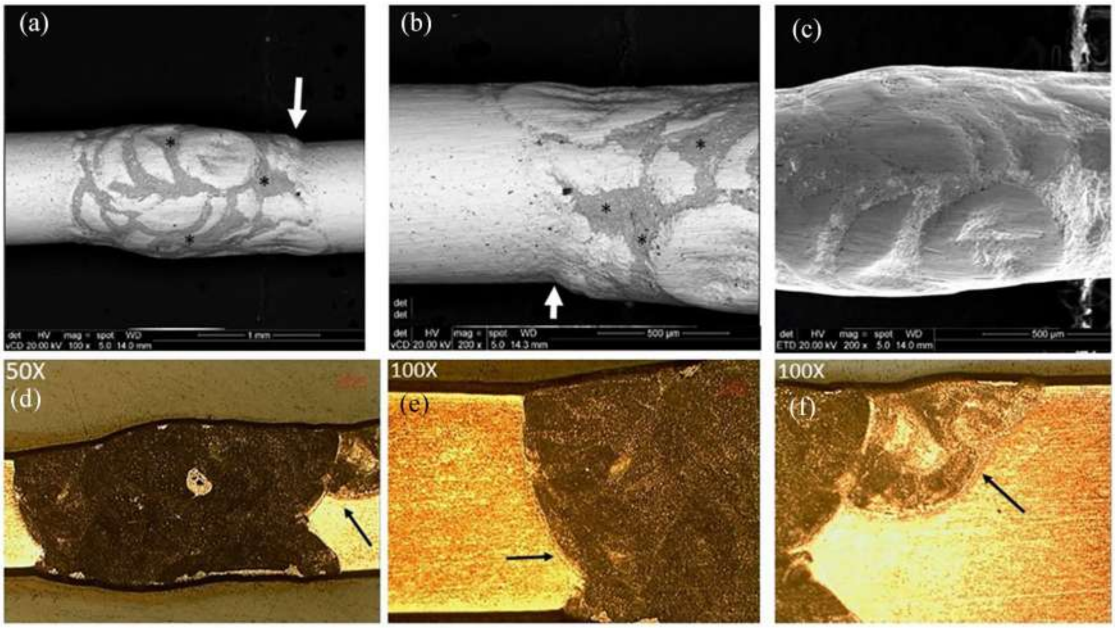


**Table 2.** Rupture sites of the wires after tensile strength.

| | Rupture site | |
|---|---|---|
| | On the weld | Near the weld |
| Tungsten inert gas | 10 | 0 |
| Laser | 0 | 10 |
| Spot | 10 | 0 |
| Silver | 8 | 2 |

The highest tensile strength mean values were obtained by silver soldering (532 N), followed by laser (420 N), spot (301 N) and TIG (296 N) welding (Table 1). SEM and metallography images are shown in Figures 3–6.

The analysis of the wires after tensile strength test revealed that rupture occurred in the weld region for all TIG and spot joints. Fracture occurred in the wire near the weld region on eight samples with silver joints and immediately adjacent to it on two, with fracture of a small portion of the weld region. Laser-welded wires had all ruptures occurring very close to the weld, without involving it (Table 2).

## Discussion

The original tensile strength of the 0.8-mm orthodontic wire averages 1492 ± 55 N according to the manufacturer's specifications. All welding techniques altered the original properties of the wires, with significant differences between the methods. Despite this reduced resistance, all techniques generated structures strong enough to withstand orthodontic forces (Mathew et al., 2016; Mesquita et al., 2018; Muguruma et al., 2018).

Mechanical tests were performed in this study, similar to others in the literature (Bock et al., 2008a, 2008b, 2009; Heidemann et al., 2002; Nascimento et al., 2012; Sestini et al., 2006; Muguruma et al., 2018). Metallographic and morphologic evaluations were carried out to analyse the visual quality of joints, providing information for better interpretation of the tensile strength results. Metallography allows a broader understanding of the morphological and structural characteristics of the joints. This analysis served as a tool for comparing between groups and identifying possible causes for the mechanical performance. Changes in the microstructure appear in all photomicrographs of the soldered specimens. The SEM morphologic evaluation used BSE and SE imaging.

In silver welding, the segments are completely covered without melting the steel, forming a micromechanical union (Figure 3). On the other hand, in TIG and laser welding, a new structure is formed with the melting of the segments (Figures 5 and 6). The spot technique provides partial joining of the wires (Figure 4). Thus, BSE images of the silver solder reveal different compositions between the wire and the welded region (Figure 3). This composition is not observed in the other techniques where there is electron sharing with fusion between the segments (Figures 4–6). Laser images present irregular dark areas in the weld region, probably compatible with chromium oxide, suggesting structure oxidation despite the inert gas coating.

The higher tensile strength values were obtained by silver soldering, which is in agreement with previous results (Muguruma et al., 2018). Higher resistance values have been found for TIG and laser (Bock et al., 2008a). TIG and laser welding presented a low standard deviation, indicating a more standardised technique, while silver welding presented a high standard deviation. The high standard deviation sheds light on the difficulty of performing conventional soldering, which has great individual variability. This may be considered a weakness of this technique.

Spot, TIG and laser welding are less individual-dependent processes with higher ease of operation (Perveen et al., 2018). These alloy-free methods generate appliances with lower corrosive potential. The ease of operation and the generation of appliances with higher biocompatibility are advantages of these techniques. However, the tensile strength of TIG and spot-welded joints was significantly lower. Spot welding requires overlapping joints and is most efficient when joining thin sections of materials, such as wires and molar bands (ISO 9333:2006; Perveen et al., 2018). Despite using the same settings, irregular and superficial penetration depth points were observed for spot welding (MEV). It is possible that the high diameter and positioning of the 0.8-mm round wires are responsible for this variation, as stabilisation of these wires is difficult when pressed by the electrodes. The weak tensile strength presented by the spot joints may also be related to the number of welded points. We performed two weld points at each joint, according to the size of the region to be welded. However, the increase in the number of weld points may possibly increase the resistance values (Nascimento et al., 2012). Due to these limitations in the high diameter of the wire and the number of points, it is not viable to extrapolate our findings to the expected performance of welded wires of smaller diameters or rectangular section, nor for welding in molar bands. These surfaces may present higher strengths than those found in our study.

Large heat-affected zones were observed on TIG joints, corroborating previous reports (Da Silveira et al., 2012; Perveen et al., 2018; Wang and Welsch, 1995). Failures observed (Figure 5) are probably associated with the complex metallurgical transformations after exposure to high temperature. These findings may explain the lower mechanical performance of the wires and breakage in the weld region.

Laser is presented as the most efficient welding method in dentistry (Perveen et al., 2018; Muguruma et al., 2018). Its concentrated heat source causes less distortion and narrow heat-affected zone, producing a higher-quality joint

(Perveen et al., 2018). This was confirmed in our study. Despite laser presenting lower strength than silver joints, there was no statistically significant difference ($P = 0.320$). Limitation of this technique lies in the higher cost of the equipment and laboratory process.

TIG is used for joining dental alloys and can offer high-quality joints (Perveen et al., 2018) but has not been routinely used in orthodontics. In our study, the outcomes of TIG welding, yet possibly suitable for clinical use, were below expectation. Considering that TIG is a low-cost alternative, when compared with laser welding, and that small modifications during this process may significantly influence the outcomes (Bock et al., 2008b), a broader understanding (Schacher and De Menezes, 2020) and definition of optimal welding parameters may enable and expand this technique for orthodontic use.

The purpose of this study was to test alternative methods for welding, looking at more biocompatible appliances. Mechanical tests are important tools to evaluate metallic structures, but the results have limitations. Considering their in vitro nature, the conditions vary greatly from clinical situations. Exposure of the appliances to the oral environment, with pH variations (Muguruma et al., 2018), chewing efforts and aging of the materials, may alter their performance (Soteriou et al., 2014). Moreover, the tensile strength result gives an idea of the structure's behaviour, but it is not possible to assume that the values refer to the weld strength specifically (Matsunaga et al., 2015). Factors such as wire heating and presence of porosities may be significant for tensile performance, and the results should correlate with microstructural changes of each welding method. Whilst all methods of welding are strong enough to withstand orthodontic forces, it would be worthwhile in future to consider if this can be conducted *in vivo*. New studies are indicated for a broader understanding of the clinical performance of different welded appliances with more biocomatible characteristics.

## Conclusion

Laser welding strength is high and comparable to silver welding. Spot and TIG welding techniques present comparable and significantly lower strengths. Despite the differences, the four welding methods presented resistance values compatible with orthodontic use in this in vitro study.

The microstructural morphology is different for each welding technique. A new structure is formed for laser and TIG methods, while for conventional brazing the segments are covered in a micromechanical union. The spot technique provides partial joining of the wires. The association between the mechanical performance and the microstructure evaluation allowed us to conclude that laser presented the highest-quality joint.

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## Declaration of conflicting interests

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