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Influence of different brazing and welding methods on tensile strength and microhardness of orthodontic stainless steel wire

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SUMMARY The aim of this study was to compare the mechanical strength and microhardness of joints made by conventional brazing and tungsten inert gas (TIG) and laser welding. A standardized end-to-end joint configuration of the orthodontic wire material in spring hard quality was used. The joints were made using five different methods: brazing (soldering > 450°C) with universal silver solder, two TIG, and two laser welders. Laser parameters and welding conditions were used according to the manufacturers' guidance. The tensile strengths were measured with a universal testing machine (Zwick 005). The microhardness measurements were carried out with a hardness tester (Zwick 3202). Data were analysed using one-way analysis of variance and Bonferroni's *post hoc* correction ($P < 0.05$).

In all cases, brazing joints ruptured at low levels of tensile strength (198 ± 146 MPa). Significant differences ($P < 0.001$) between brazing and TIG or laser welding were found. The highest means were observed for TIG welding (699–754 MPa). Laser welding showed a significantly lower mean tensile strength (369–520 MPa) compared with TIG welding. Significant differences ($P < 0.001$) were found between the original orthodontic wire and the mean microhardness at the centre of the welded area. The mean microhardness differed significantly between brazing (1.99 GPa), TIG (2.22–2.39 GPa) and laser welding (2.21–2.68 GPa).

For orthodontic purposes, laser and TIG welding are solder-free alternatives to joining metal. TIG welding with a lower investment cost is comparable with laser welding. However, while expensive, the laser technique is a sophisticated and simple method.

Introduction

The joining of a metal framework is frequently necessary to create individual orthodontic appliances and to achieve efficient treatment procedures. Brazing, defined as soldering at a temperature of more than 450°C, is the conventional method of joining orthodontic wires in different clinical situations (Gulker *et al.*, 1994; Gawlik *et al.*, 1996; Chaves *et al.*, 1998; Heidemann *et al.*, 2002; Dua and Nandlal, 2004). Besides the problems of galvanic corrosion and biocompatibility, brazing gaps show a low mechanical strength with high failure rates (Scroggs *et al.*, 1992; McCartney and Doud, 1993; Oda and Okabe, 1996; Anselm Wiskott *et al.*, 2001; Mockers *et al.*, 2002; Solmi *et al.*, 2004; Yokota *et al.*, 2004; Sestini *et al.*, 2006; Yan and Yang, 2006; Zupancic *et al.*, 2006).

Another method employed for joining metal frameworks is laser welding (Berg *et al.*, 1995; Tambasco *et al.*, 1996; Chai and Chou, 1998; Taylor *et al.*, 1998; Wang and Chang, 1998; Baba *et al.*, 2004; Krishnan and Kumar, 2004; Baba and Watanabe 2005; Uysal *et al.*, 2005; Verstrynge *et al.*, 2006). To weld dental alloys, crystals of yttrium, aluminium, and garnet with added neodymium are mainly used to emit laser beams (Yamagishi *et al.*, 1993; Liu *et al.*, 2002; Iwasaki *et al.*, 2004; Watanabe and Topham, 2004, 2006; Srimaneepong *et al.*, 2005; Watanabe *et al.*, 2006).

In 2005, an alternative with lower investment costs was introduced in orthodontics. Based on the well-known tungsten inert gas (TIG) welding, two different devices for orthodontic purposes were developed (Rocha *et al.*, 2006). The welding heat is produced by a light bow between tungsten anode and metal. The advantages of laser and TIG welding systems can be summarized as follows: no solder and thus no galvanic corrosion at the joint, small focus, a stereomicroscope for efficient working and an argon-shielding atmosphere to prevent the oxidation around the welding zone (Jelmert *et al.*, 1995; Solmi *et al.*, 2004; Sestini *et al.*, 2006).

Therefore, the aim of this study was to compare the mechanical strength and the microhardness of joints made using conventional brazing and TIG and laser welding.

Materials and methods

A standardized end-to-end joint configuration of the orthodontic wire (Forestanit Lot: 272; Forastadent, Pforzheim, Germany) in spring hard quality (diameter 1.2 mm) was used. The joints were made using five different methods: brazing with universal silver solder, OrthoPhaser (Dentaurum, Ispringen, Germany), Welder (Schütz Dental, Rosbach, Germany), DL 2002 (Dentaurum), and LWI (Schütz Dental). Laser parameters and welding conditions were used in accordance with the manufacturers' specifications (Table 1). Two different laser and TIG welding parameters of the devices made by Schütz Dental were tested. For each joining method, 10 specimens were produced.

The tensile strength measurement of different welding and brazing methods was carried out using a universal testing machine (Zwick 005, Zwick GmbH & Co. KG, Ulm, Germany). The wire length between the crossheads of the machine was set to a level of 5 mm. The full-scale load was set at 2000 N with a crosshead speed of 10 mm/minute.

The microhardness measurements were carried out with a hardness tester Zwick 3202 with a diamond indenter after Vickers. All measurements were conducted with a test load of 100 mN, an impact speed of 4 mm/minute and a loading period of 15 seconds. The evaluation took place via light–optical measurement of the diagonal length.

The data were analysed using the Statistical Software Package for Social Sciences (SPSS Inc., Chicago, Illinois, USA) version 12.0 and the use of one-way analysis of variance (ANOVA) and Bonferroni's *post hoc* test. The level of significance was set at 5 per cent.

Results

Means, minimum, maximum, and standard deviations (SDs) of the tensile strength of the different joining methods were calculated and are summarized in Table 2. The mean tensile strength of the original orthodontic wire (1493 ± 39 MPa) was found to be in agreement with the manufacturers' specifications. Compared with these findings, welding and brazing significantly decreased the tensile strength (ANOVA, $P < 0.001$, Table 2). The highest means were observed for TIG welding (699–754 MPa) with low SDs. No significant differences were found between the welding devices and welding parameters (Bonferroni's *post hoc* test, $P > 0.05$, Table 2).

Laser welding showed a significantly lower mean tensile strength (369–520 MPa) compared with TIG welding (Bonferroni's *post hoc* test, $P < 0.05$, Table 2). No significant differences were found between the laser welding groups.

Brazing demonstrated the lowest mean tensile strength (198 ± 146 MPa) with a high SD. The tensile strength of seven specimens was lower than 350 MPa.

The mean microhardness of the Forestanit wire (spring hard quality) was measured at 3.79 ± 0.09 GPa (Figure 1a–c). In the heat-affected zone adjacent to the welding or brazing area, the wire showed a slight increase in hardness (up to 4.68 GPa, Figure 1a–c). In the joining area, the microhardness decreased (up to 1.47 GPa, Figure 1a–c). The lowest mean microhardness was found with brazing (1.99 ± 0.30 GPa) and the highest level with laser welding (Laser 2: 2.68 ± 0.14 GPa; Table 3).

Generally, significant differences were found between the original orthodontic wire and the mean microhardness at the centre of the joining area (ANOVA, $P < 0.001$). The mean microhardness significantly differed between brazing and TIG or laser welding (Bonferroni's *post hoc* test, $P < 0.05$; Table 3).

Table 1 The joining methods used (TIG, tungsten inert gas welding; laser, laser welding). Welding parameters are accordance with the manufacturers' specifications. Welding joints were made by the manufacturers of the TIG or laser devices.

Brazing	Silver solder (Lot: 47160)	Dentaurum (Ispringen, Germany)
TIG 1	OrthoPhaser (70%, 21 ms)	Dentaurum
TIG 2	Welder (P4 30 ms)	Schütz Dental (Rosbach, Germany)
TIG 3	Welder (P6 35 ms)	Schütz Dental
Laser 1	Desktop Power Laser [265 V 3 ms (1.4 Hz) 0.4 mm]	Dentaurum
Laser 2	LWI (P2 5 ms 0.9 mm)	Schütz Dental
Laser 3	LWI (P2 5 ms 1.2 mm)	Schütz Dental

Discussion

Recently, Solmi *et al.* (2004) analysed the adhesion and proliferation of human gingival fibroblasts placed in direct contact with conventionally soldered and laser-welded orthodontic joints for up to 16 days. Significant differences in counts of survival fibroblasts were observed at all

Table 2 Tensile strength in megapascals (n, number of specimens; SD, standard deviation; SE, standard error; min, minimum; max, maximum). TIG, tungsten inert gas welding; laser, laser welding. Results of Bonferroni's *post hoc* test (ns, non-significant).

	n	Means	SD	SE	Min	Max	Original	Solder	TIG 1	TIG 2	TIG 3	Laser 1	Laser 2	Laser 3
Original	10	1493.34	39.16	14.52	1477.28	1634.33		***	***	***	***	***	***	***
Brazing	10	197.72	145.89	46.14	32.98	399.20	***		***	***	***	**	**	***
TIG 1	10	724.45	61.57	19.47	590.73	828.37	***	***		ns	ns	***	***	**
TIG 2	10	698.59	83.46	27.82	594.32	897.99	***	***	ns		ns	***	***	*
TIG 3	10	754.03	78.14	29.53	666.86	868.31	***	***	ns	ns		***	***	**
Laser 1	10	402.04	128.20	40.54	252.46	566.47	***	**	***	***	***		ns	ns
Laser 2	10	369.41	59.32	18.76	255.23	437.75	***	**	***	***	***	ns		ns
Laser 3	10	519.73	69.67	28.44	457.32	644.80	***	***	**	*	**	ns	ns	
Overall	80	646.58	401.45	47.31	32.98	1634.33								

Level of significance: $^*P \leq 0.05$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$.

Table 3 Microhardness in gigapascals at the centre of the joining area (*n*, number of specimens; SD, standard deviation; SE, standard error; min, minimum; max, maximum). TIG, tungsten inert gas welding; laser, laser welding. Results of Bonferroni's *post hoc* test (ns, non-significant).

	n	Means	SD	SE	Min	Max	Original	Solder	TIG 1	TIG 2	TIG 3	Laser 1	Laser 2	Laser 3
Original	10	3.79	0.09	0.04	3.39	3.80		***	***	***	***	***	***	***
Brazing	10	1.99	0.30	0.10	1.62	2.62	***		**	ns	*	***	***	**
TIG 1	10	2.39	0.20	0.07	2.17	2.72	***	**		ns	ns	ns	ns	*
TIG 2	10	2.22	0.12	0.04	2.08	2.42	***	ns	ns		ns	ns	ns	***
TIG 3	10	2.22	0.10	0.03	2.05	2.43	***	*	ns	ns		ns	ns	***
Laser 1	10	2.43	0.16	0.05	2.16	2.74	***	***	ns	ns	ns		ns	ns
Laser 2	10	2.23	0.09	0.02	2.05	2.43	***	**	ns	ns	ns	ns		***
Laser 3	10	2.68	0.14	0.05	2.52	2.93	***	***	*	***	***	ns	***	
Overall	80	2.45	0.52	0.06	1.62	3.80								

Level of significance: $^{*}P \leq 0.05$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$.

experimental times. The fibroblasts on both the laser-welded and control substrates showed similar patterns. By contrast, on the substrate of the soldered samples, the fibroblasts showed no sign of adaptation at any time during the study. These results highlight the superior biocompatibility of laser welding over brazing. Furthermore, Mockers *et al.* (2002) characterized orthodontic materials as non-cytotoxic except silver-soldered joints. Testing the cell reactions of osteoblasts, fibroblasts, and keratinocytes, Sestini *et al.* (2006) found a good tolerance of electrical resistance and laser welding, while traditional silver solder was toxic for osteoblast differentiation, fibroblast viability, and keratinocyte growth.

Studies concerning the mechanical and microhardness characteristics of welded or soldered orthodontic wires are rare making direct comparison of different brazing and welding methods difficult. The results of tensile strength measurements of welded precious and non-precious cast alloys used in fixed or removable prosthodontics can be transferred for orthodontic purposes, but with limitations (Gawlik *et al.*, 1996; Mockers *et al.*, 2002; Krishnan and Kumar, 2004).

The influence of brazing or welding on tensile strength has not been uniformly determined. In different studies, the factors affecting the mechanical strength of welded joints have been described: wavelength, peak pulse power, pulse energy, output energy, pulse duration, pulse frequency, and spot diameter of the laser welding machine and the type of metal used (McCartney and Doud, 1993; Yamagishi *et al.*, 1993; Taylor *et al.*, 1998; Watanabe *et al.*, 2001, 2003, 2004, 2006; Yan and Yang, 2006). Chai and Chou (1998) showed an equal or superior (range 374–562 MPa) mechanical strength of the welded sites compared with the unsectioned parent metal (540 ± 11 MPa) of different Ti alloys depending on welding conditions. In contrast, the fracture load of unwelded Ti, gold, or Co–Cr alloys in different configurations of laser welding was not achieved (Watanabe *et al.*, 2001, 2003, 2004, 2006). Especially for gold and Co–Cr alloys, only 50 per cent or less of the original measurements were found. In the study by Bertrand *et al.* (2004), a small change in the chemical composition of the Ni-based alloys caused an important difference in weldability.

Rocha *et al.* (2006) compared laser and TIG welding of non-precious alloys. TIG welding increased the flexural strength of Ti, Co–Cr, and Ni–Cr as the used welded cylinders presented higher flexural strength than the non-weld cylinders. The highest means were observed for Co–Cr weld by TIG (2665 ± 281 MPa) and non-welded Co–Cr (2654 ± 64 MPa; Rocha *et al.*, 2006). By contrast, laser welding (464 ± 70 MPa) achieved only 17.5 per cent of the flexural strength of Co–Cr alloy. When joining Co–Cr alloy specimens, Zupancic *et al.* (2006) showed significant differences between brazing (792 MPa) and laser welding (405 MPa). Those authors estimated a low penetration depth, peripheral overheating, porosities, and carbon content of the alloy as possible reasons for the relative weakness of laser welding.

The evaluation of three orthodontic arch wire alloy materials, stainless steel, beta titanium, and Timolium, for their laser-weld characteristics showed significantly different tensile strength values between these materials (stainless steel 363 ± 22 MPa, beta titanium 463 ± 27 MPa, and Timolium 344 ± 25 MPa; Krishnan and Kumar, 2004). Although a comparison with original wires was not carried out in that study, it could be assumed that laser-welded specimens showed a significantly lower tensile strength than pure metals (approximately 1500–1800 MPa).

The influence of used orthodontic wire material in the case of brazing was examined in the study by Dua and Nandlal (2004). The mean tensile strength values of soldered joints for various wire groups differed significantly. Gloria (stainless steel) wire had a lower tensile strength compared with Remanium (stainless steel) and Remaloy (Co–Cr) orthodontic wires.

In the present investigation, a direct comparison between brazing and TIG and laser welding was realized for the first time. Brazing demonstrated the lowest mean tensile strength with 70 per cent of the specimens not fulfilling the minimum of 350 MPa. TIG and laser welding showed significantly

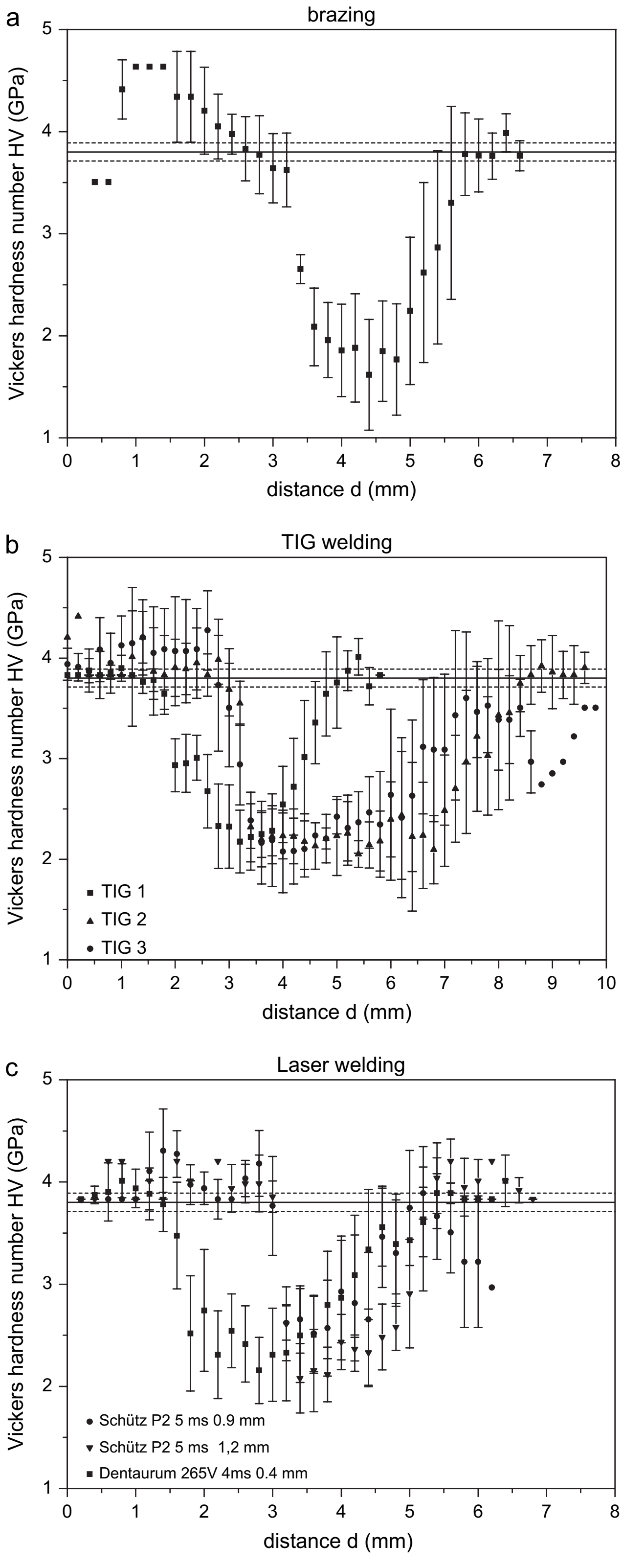

Figure 1 Graphical analysis of microhardness [Vickers hardness in gigapascals (GPa)] for (a) brazing. (b) tungsten inert gas (TIG), and (c) laser welding. Lines at 3.79 ± 0.09 GPa: mean and standard deviation of original wire.

higher mean values for tensile strength, but the tensile strength of the original wire was not achievable. Therefore, welding changed the material attributes, and the loss of spring hard quality has to be considered in planning orthodontic treatment.

Determination of the microhardness of the Ni–Cr–Mo and Co–Cr–Mo alloys showed that the central part of the weld had a higher hardness (Remanium CS 340 ± 30 GPa) than the cast metal (220 ± 20 GPa). Similar results for titanium were reported by Uysal *et al.* (2005). Other authors pointed out that this was probably due to the refining in the grain size and the substructure which appears during the rapid solidification stage (Bertrand *et al.*, 2004; Zupancic *et al.*, 2006). Furthermore, while testing orthodontic wire materials using brazing and laser and TIG welding, a completely different behaviour in microhardness could be observed in the present investigation. Comparable studies were not available. The microhardness of the original wire was in the same range as that reported by Verstrynge *et al.* (2006). In laser welding, a slight tendency for a correlation between a higher mean microhardness and higher tensile strength was observed.

Conclusion

Tensile strength and microhardness of TIG welding is comparable with laser welding and is a low cost and solder-free alternative for orthodontic purposes.

Small changes in TIG or laser welding parameters significantly influenced the mechanical properties of orthodontic wires. Further investigations are needed to determine the optimal welding parameters for each of the devices and different joining methods.

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