Original Article

Deflection load characteristics of laser-welded orthodontic wires

Etsuko Watanabe[a]; Garrett Stigall[b]; Waleed Elshahawy[c]; Ikuya Watanabe[d]

ABSTRACT

Objective: To compare the deflection load characteristics of homogeneous and heterogeneous joints made by laser welding using various types of orthodontic wires.

Materials and Methods: Four kinds of straight orthodontic rectangular wires (0.017 inch × 0.025 inch) were used: stainless-steel (SS), cobalt-chromium-nickel (Co-Cr-Ni), beta-titanium alloy (β-Ti), and nickel-titanium (Ni-Ti). Homogeneous and heterogeneous end-to-end joints (12 mm long each) were made by Nd:YAG laser welding. Two types of welding methods were used: two-point welding and four-point welding. Nonwelded wires were also used as a control. Deflection load (N) was measured by conducting the three-point bending test. The data ($n = 5$) were statistically analyzed using analysis of variance/Tukey test ($P < .05$).

Results: The deflection loads for control wires measured were as follows: SS: 21.7 ± 0.8 N; Co-Cr-Ni: 20.0 ± 0.3 N; β-Ti: 13.9 ± 1.3 N; and Ni-Ti: 6.6 ± 0.4 N. All of the homogeneously welded specimens showed lower deflection loads compared to corresponding control wires and exhibited higher deflection loads compared to heterogeneously welded combinations. For homogeneous combinations, Co-Cr-Ni/Co-Cr-Ni showed a significantly ($P < .05$) higher deflection load than those of the remaining homogeneously welded groups. In heterogeneous combinations, SS/Co-Cr-Ni and β-Ti/Ni-Ti showed higher deflection loads than those of the remaining heterogeneously welded combinations (significantly higher for SS/Co-Cr-Ni). Significance ($P < .01$) was shown for the interaction between the two factors (materials combination and welding method). However, no significant difference in deflection load was found between four-point and two-point welding in each homogeneous or heterogeneous combination.

Conclusion: Heterogeneously laser-welded SS/Co-Cr-Ni and β-Ti/Ni-Ti wires provide a deflection load that is comparable to that of homogeneously welded orthodontic wires. (*Angle Orthod.* 2012;82:698–702.)

KEY WORDS: Orthodontics; Wire; Titanium; Laser; Welding

INTRODUCTION

Orthodontic wires, which generate the biomechanical forces communicated through brackets for tooth movement, are composed of four major base metal alloy types[1,2]: stainless steel (SS), cobalt-chromium-nickel (Co-Cr-Ni), nickel-titanium (Ni-Ti), and β-Ti. SS wires have excellent formability along with high mechanical properties (high strength and high modulus of elasticity).[3–6] Co-Cr-Ni wires also have high elastic modulus and can easily be manipulated into desired shapes and then heat-treated to achieve considerable increases in strength and resilience.[2,6] Both SS and Co-Cr-Ni wires can be soldered and welded for the fabrication of complex appliances. Ni-Ti wires, which contain approximately equiatomic proportions of Ni and Ti, offer a modulus of elasticity that is nearly one-fifth that of the SS wires, along with very wide elastic working range.[1,2] The Ni-Ti wires possess superelasticity and shape-memory effect.[7,8] The β-Ti wires were conceived for

[a] Assistant Professor, Department of Dental and Biomedical Materials Science, Nagasaki University Graduate School of Biomedical Science, Nagasaki, Japan.

[b] Undergraduate student, Texas A&M Health Science Center, Baylor College of Dentistry, D3, Dallas, Tex.

[c] Assistant Professor, Department of Conservative Dentistry, Faculty of Dentistry, Tanta University, Tanta, Egypt.

[d] Professor and Department Chair, Department of Dental and Biomedical Materials Science, Nagasaki University Graduate School of Biomedical Science, Nagasaki, Japan.

Corresponding author: Dr Etsuko Watanabe, Department of Dental and Biomedical Materials Science, Nagasaki University Graduate School of Biomedical Science, 1-7-1 Sakamoto, Nagasaki, 852-8588, Japan
(e-mail: ewatana@nagasaki-u.ac.jp)

Accepted: September 2011. Submitted: June 2011.
Published Online: November 1, 2011

 DOI: 10.2319/061411-393.1

Table 1. Elemental Composition (wt.%) for the Wires[a]

	Fe	Co	Cr	Ni	Mn	Ti	Sn	Zr	Mo
Stainless steel	69.5	0.75	18.5	9.0	1.0	–	–	–	–
Co-Cr-Ni	15.83	39.8	19.9	15.4	1.97	–	–	–	7.1
β-Ti	–	–	–	–	–	62–81.75	3.75–8	4.5–10	10–20
Ni-Ti	–	–	–	55	–	45	–	–	–

[a] Data from information by the manufacturer. Fe indicates iron; Co, cobalt; Cr, chromium; Ni, nickel; Mn, manganese; Ti, titanium; Sn, tin; Zr, zirconium; Mo, molybdenum.

orthodontic use about three decades ago and offer a modulus of elasticity measuring approximately half that of the SS wires.[3–5] Because the β-Ti wires offer good mechanical properties, namely, excellent formability and excellent corrosion resistance (Ni-free), they are widely used, especially for patients in orthodontics with an allergy to Ni. However, these Ti alloy (Ni-Ti and β-Ti) wires are difficult to join by soldering and welding as a result of the high reactivity of Ti with gasses such as oxygen and nitrogen at high temperatures.[9,10] Therefore, soldering and welding of Ti and its alloys can only be performed under vacuum or argon atmosphere.[11,12] However, there are several research reports[13–16] about the welding of Ti alloy wires using conventional dental welding. These studies imply the possibility of welding for Ti alloy orthodontic wires.

One of the methods of joining Ti and its alloys is laser welding under argon shielding.[12] Laser welding is a convenient method with which to connect any type of dental alloys, especially Ti, because Ti has higher laser beam absorption and lower thermal conductivity (high heat absorption in small area) than do the other dental alloys.[17] The advantages of laser welding include the following: there are fewer heat effects on the surrounding area to be welded, and no materials (such as investment materials, furnace, and gas torch) are necessary for conventional dental soldering.[18] Another advantage of laser welding is that it allows welding of different types of dental alloys regardless of the different melting points for the alloys.[19,20] In general, alloys with similar compositional elements could produce favorable results for the welding of different alloys because of the similarity of their melting points. Although the use of laser welding has become widespread in prosthodontics, there are few reports[21–23] regarding the laser welding of orthodontic wires. Furthermore, no other investigation has been performed regarding the laser welding of different types of orthodontic wires, as stated above.

The significance of laser welding of orthodontic wires is that the force and torque applied for tooth movement can be controlled by welding different sizes, shapes (square, rectangular, round, and twist), and types of orthodontic wires. Note that prefabricated combination archwires with a rectangular anterior segment and a round posterior segment have recently become commercially available for Ni-Ti, β-Ti, and SS used in clinical orthodontics. Therefore, the objective of this study is to investigate the deflection load characteristics of homogeneous and heterogeneous joints made by laser welding using four types of orthodontic wires.

MATERIALS AND METHODS

Four types of rectangular wire (0.017 inch × 0.025 inch) were used: SS (STSS1725, (G&H Wire Company, Greenwood, Ind); Co-Cr-Ni (Colboloy, STRCB1725, G&H Wire Company); β-Ti (BT3, SBT3-1725, G&H Wire Company); and Ni-Ti (SENT1725, G&H Wire Company). The elemental compositions of the wires are shown in Table 1.

Specimen Preparation for Three-Point Bending Test

The 12-mm–long wires were cut from each type of straight wire using a low-speed diamond saw (Isomet, Buehler, Lake Bluff, Ill) with water cooling. After the cut surfaces were polished with silicon-carbide paper (No. 400), cut surfaces of two wires were abutted against each other and fixed in a custom-made jig (Figure 1). They were then laser welded using a dental laser-welding machine (Neo-Laser L, Girrbach Co, Pforzheim, Germany) under argon gas shielding.

Homogeneous end-to-end joint specimens were prepared for each type of wire, and heterogeneous

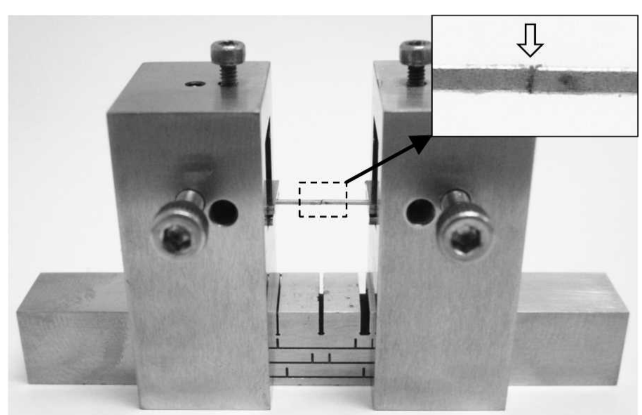

Figure 1. Custom-made jig to hold the abutted wires (an arrow in magnified picture in right upper corner).

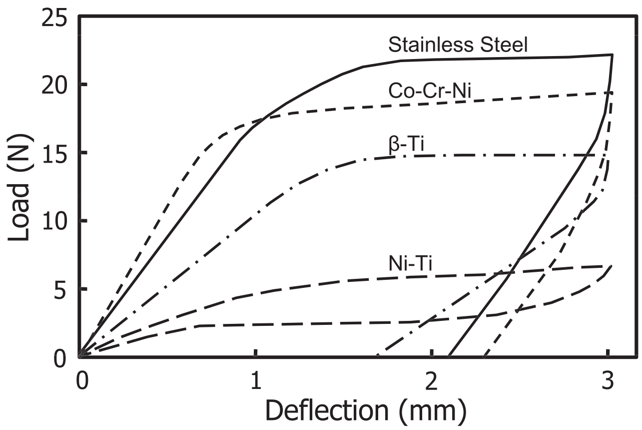

Figure 2. Deflection/load hysteresis curves of four types of wires (each curve from representative control specimen).

end-to-end joint specimens were made in combination with four types of wires. Two types of welding methods were used: two-point welding (one point on each 0.025-inch surface) and four-point welding (two points were added on each 0.017-inch surface). The pulse duration and output voltage for laser welding were fixed at 5 ms and 150 V, respectively. The spot diameters used were 0.7 mm for the 0.025-inch surface and 0.5 mm for the 0.017-inch surface, respectively. Nonwelded wires (24 mm long) were also prepared as controls.

Three-Point Bending Test

A three-point bending test (ADA Specification No. 32) was conducted using a servo-hydraulic testing machine (Minibionix II, MTS Systems Corporation, Eden Prairie, Minn) at a loading speed of 0.5 mm/min. The supported span (distance between supported rods) was 12 mm, and the load was directly applied on the laser-welded portion of the 0.025-inch surface at the middle of the 12-mm span. Each specimen was loaded until the maximum deflection of 3 mm. After 3 mm of deflection, the load reversed to the original (zero) point at the same loading speed. The loads at maximum deflection (maximum deflection loads) were measured for the control and laser-welded specimens. When the specimens were fractured before the maximum deflection at 3 mm, the loads at fracture were recorded as the maximum deflection load for laser-welded specimens. The data (n = 5) for maximum deflection loads were statistically analyzed using analysis of variance/Tukey test ($P < .05$).

RESULTS

The load/deflection curves of the control specimens are presented in Figure 2. The highest maximum deflection was obtained for SS wire (21.7 $\pm$ 0.8 N), followed by Co-Cr-Ni (20.0 $\pm$ 0.3 N), β-Ti (13.9 $\pm$ 1.3 N), and Ni-Ti (6.6 $\pm$ 0.4 N) wires. The curve of Ni-Ti showed superelasticity (the curve returned to the starting zero point).

The deflection loads for two-point welding and four-point welding are presented in Table 2 (homogeneously welded combinations) and Table 3 (heterogeneously welded combinations) and depicted in Figure 3 (two-point welding) and Figure 4 (four-point welding), respectively. All of the homogeneously welded wires showed lower deflection loads compared to the corresponding control wires and exhibited higher deflection loads compared to the heterogeneously welded combinations. In the homogeneous combinations, Co-Cr-Ni/Co-Cr-Ni showed a significantly ($P < .05$) higher deflection load than did the remaining homogeneously welded groups. Most of the homogeneously welded specimens deflected to the maximum deflection (3 mm), except for the two-point welding of SS, Co-Cr-Ni, and Ni-Ti, in which a few specimens fractured right before the maximum deflection of 3 mm. None of the β-Ti/β-Ti specimens for both two-point and four-point welding methods fractured before the maximum deflection. Figure 5 shows the load/deflection curves of homogeneously welded wires (four-point welding). The highest deflection load of the homogeneously welded specimens was obtained for Co-Cr-Ni. The maximum deflection loads of SS/SS dropped down and reached a level similar to that of β-Ti/β-Ti. In heterogeneous combinations, SS/Co-Cr-Ni and β-Ti/Ni-Ti showed higher deflection loads than did the remaining heterogeneously welded combinations (significantly higher for SS/Co-Cr-Ni). Most of the heterogeneously welded specimens fractured during the three-point testing, except for the SS/Co-Cr-Ni combinations, in which most of the specimens deflected at the maximum deflection.

Significance ($P < .01$) was found for the interaction between the two factors (materials combination and welding method) in both of the homogeneous and heterogeneous combinations. However, no significant difference in deflection load was found between four-point and two-point welding in either homogeneous or heterogeneous combinations, even though the four-point welding group showed a slightly higher deflection load

Table 2. Deflection Loads (N) of Homogeneously Welded Combinations[a]

		Stainless Steel	Co-Cr-Ni	β-Ti	Ni-Ti
Control		21.7 (0.8)	20.0 (0.3)	13.9 (1.3)	6.6 (0.4)
Welding methods	Two-point welding	8.0 (0.5)*	11.2 (2.2)	8.0 (0.8)*	5.5 (0.5)
	Four-point welding	7.1 (1.6)**	13.0 (0.3)	9.1 (0.3)	5.8 (0.1)**

[a] * and ** indicate no statistical difference ($P > .05$) in the same row. Value for $\pm$1 standard deviation (SD) in parentheses. Co indicates cobalt; Cr, chromium; Ni, nickel; and Ti, titanium.

Table 3. Deflection Loads (N) of Heterogeneously Welded Combinations[a]

	SS/Co-Cr	SS/β-Ti	SS/Ni-Ti	Co-Cr/β-Ti	Co-Cr/Ni-Ti	β-Ti/Ni-Ti
Two-point welding	7.1 (0.1)	2.7 (0.7) AB	1.7 (0.3) B	2.6 (1.0) AB	3.4 (1.6) AC	5.0 (0.4) C
Four-point welding	9.2 (1.4)	2.4 (0.1) AB	1.7 (0.3) A	3.6 (1.8) AB	4.2 (1.2) B	4.3 (0.5) B

[a] Identical online letters in the same row indicate no statistical difference ($P > .05$). Value for ±1 standard deviation (SD) in parentheses. SS indicates stainless steel; Co, cobalt; Cr, chromium; Ti, titanium; and Ni, nickel.

than did the corresponding two-point welding group in most groups.

DISCUSSION

All homogeneous welded groups except for the Ni-Ti/Ni-Ti group showed highly reduced deflection loads compared to the corresponding control group. The highest reduction was observed for SS/SS (63% [two-point] to 67% [four-point] reduction), followed by Co-Cr-Ni/Co-Cr-Ni (35% [four-point] to 44% [two-point] reduction), β-Ti/β-Ti (35% [four-point] to 42% [two-point] reduction), and Ni-Ti/Ni-Ti (12% [four-point] to 17% [two-point] reduction).

When SS/SS and Co-Cr-Ni/Co-Cr-Ni are compared, SS and Co-Cr-Ni possess similar compositional elements (Table 1), except for iron (Fe) and Co. The SS is composed of 69.5% Fe with no Co, whereas the balance of Fe is 22.9% for the Co-Cr-Ni, which contains approximately 40% Co. In addition, the Co-Cr-Ni contains 7.1% molybdenum (Mo), which is not contained in the SS. Although Co and Fe have similar properties (thermal conductivity, rate of laser beam absorption, melting point, etc) that are different from those of Mo, the difference in composition for Fe, Co, and/or Mo could be the reason for the highly reduced deflection load for SS/SS vs that seen for Co-Cr-Ni/Co-Cr-Ni. In homogeneously welded Ti-based wires (β-Ti and Ni-Ti), the Ni-Ti/Ni-Ti showed a lesser reduction of deflection load than did the β-Ti. These results could be explained by the fact that the Ni-Ti wire exhibited the lowest value of elastic modulus and deflection load among the materials tested. If the Ni-Ti/Ni-Ti specimens deflected to the maximum deflection (3 mm), the maximum deflection loads of the Ni-Ti/Ni-Ti specimens will be similar to those of the control Ni-Ti, since the control Ni-Ti also exhibits the lowest elastic modulus and maximum deflection load among the controls (Figure 2). On the other hand, the proportional limit (maximum stress at elastic limit) of the β-Ti/β-Ti specimens is lowered by laser welding, therefore resulting in the reduced deflection load (35–42% reduction).

Heterogeneously welded combinations showed lower deflection loads compared to the homogeneously welded wires. In heterogeneously welded groups, SS/Co-Cr-Ni and β-Ti/Ni-Ti showed higher deflection loads than did the remaining heterogeneously welded combinations (significantly higher for SS/Co-Cr-Ni). These results indicate that the Ti-based wires do not have good affinity with SS and Co-Cr alloys. Conversely, SS vs Co-Cr-Ni and β-Ti vs Ni-Ti have an affinity for laser welding, which can possibly be attributed to the similarity of their mechanical properties or compositional elements.

When each of the Co-Cr-Ni and β-Ti wires was welded homogeneously and SS/Co-Cr-Ni was welded heterogeneously by four-point welding, they had less reduced deflection than did the corresponding combinations joined by two-point welding. These results indicate that the homogeneously welded Co-Cr-Ni and β-Ti and heterogeneously welded SS/Co-Cr-Ni might show more improved deflection loads using a two-point welding if higher laser conditions (high laser voltage and high pulse duration) were used. Regarding the

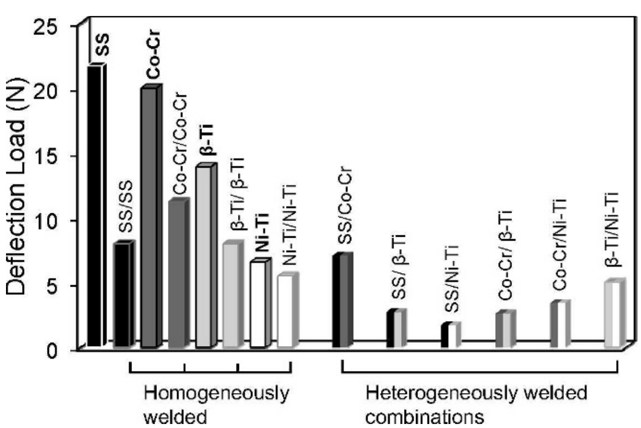

Figure 3. Maximum deflection loads for two-point welding specimens.

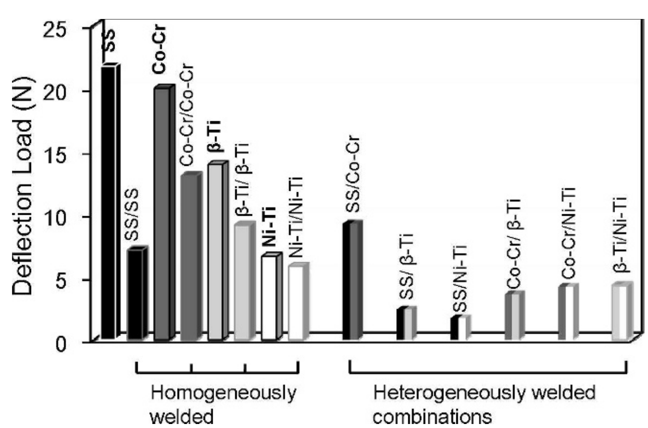

Figure 4. Maximum deflection loads for four-point welding specimens.

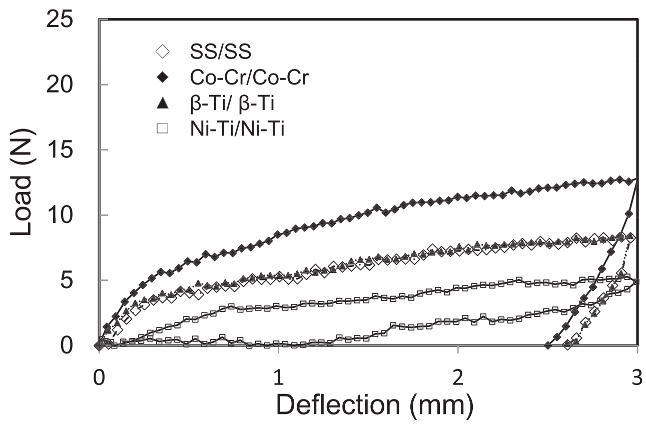

Figure 5. Deflection/load hysteresis curves of homogeneously welded wires (four-point welding).

correlation between the SS and the Co-Cr-Ni, the homogeneously welded SS using two-point welding showed slightly higher deflection load than did the heterogeneously welded SS/Co-Cr-Ni. However, using four-point welding, the deflection load of the heterogeneously welded SS/Co-Cr-Ni was higher than that of the homogeneously welded SS (in the middle between the homogeneously welded SS and the homogeneously welded Co-Cr-Ni). This is because the homogeneous four-point–welded SS had a more reduced deflection load compared to the two-point–welded SS. In addition, the heterogeneous four-point–welded SS/Co-Cr-Ni showed an improved deflection load compared with the two-point–welded SS/Co-Cr-Ni. These results indicate that the heterogeneously welded SS/Co-Cr-Ni might be affected by the welding method (four-point $>$ two-point) in conjunction with the favorable affinity between the SS and the Co-Cr-Ni for laser welding.

CONCLUSIONS

- Homogeneously laser-welded Ni-Ti showed the lowest reduction of deflection load among the wires tested.
- The heterogeneously welded combination showed lower deflection loads compared to those of homogeneously welded wires, except in the case of the SS/Co-Cr-Ni combination.
- The Ti-based orthodontic wires (β-Ti and Ni-Ti) do not have good affinity with SS and Co-Cr wires in laser welding.

ACKNOWLEDGMENT

This study was partially supported by Baylor Oral Health Foundation (Dallas, Tex).

REFERENCES

1. Asgharnia MK, Brantley WA. Comparison of bending and tension tests for orthodontic wires. *Am J Orthod*. 1986;89: 228–236.
2. Kapila S, Sachdeva R. Mechanical properties and clinical applications of orthodontic wires. *Am J Orthod Dentofacial Orthop*. 1989;96:100–109.
3. Krishnan V, Kumar KJ. Mechanical properties and surface characteristics of three arch wire alloys. *Angle Orthod*. 2004; 74:825–831.
4. Verstrynge A, Van Humbeeck J, Willems G. In-vitro evaluation of the material characteristics of stainless steel and beta-titanium orthodontic wires. *Am J Orthod Dentofacial Orthop*. 2006;130:460–470.
5. Juvvadi SR, Kailasam V, Padmanabhan S, Chitharanjan AB. Physical, mechanical, and flexural properties of 3 orthodontic wires: an in-vitro study. *Am J Orthod Dentofacial Orthop*. 2010;138:623–630.
6. Tian K, Darvell BW. Determination of the flexural modulus of elasticity of orthodontic archwires. *Dent Mater*. 2010;26: 821–829.
7. Miura F, Mogi M, Ohura Y, Hamanaka H. The super-elastic property of the Japanese NiTi alloy wire for use in orthodontics. *Am J Orthod Dentofacial Orthop*. 1986;90:1–10.
8. Yoneyama T, Doi H, Hamanaka H, Tomitsuka K, Yoshimasu H, Tanaka N, Amagasa T. Basic properties of super-elastic Ni-Ti alloy ligature wires for a new intermaxillary fixation method. *Biomaterials*. 1994;15:71–74.
9. Adachi M, Mackert JR Jr, Parry EE, Fairhurst CW. Oxide adherence and porcelain bonding to titanium and Ti-6Al-4V alloy. *J Dent Res*. 1990;69:1230–1235.
10. Watanabe I, Watkins JH, Nakajima H, Atsuta M, Okabe T. Effect of pressure difference on the quality of titanium casting. *J Dent Res*. 1997;76:773–779.
11. Liu J, Watanabe I, Yoshida K, Atsuta M. Joint strength of laser-welded titanium. *Dent Mater*. 2002;18:143–148.
12. Watanabe I, Topham DS. Laser welding of cast titanium and dental alloys using argon shielding. *J Prosthodont*. 2006;15: 102–107.
13. Donovan MT, Lin JJ, Brantley WA, Conover JP. Weldability of beta titanium arch wires. *Am J Orthod*. 1984;85:207–216.
14. Nelson KR, Burstone CJ, Goldberg AJ. Optimal welding of beta titanium orthodontic wires. *Am J Orthod Dentofacial Orthop*. 1987;92:213–219.
15. Krishnan V, Kumar KJ. Weld characteristics of orthodontic archwire materials. *Angle Orthod*. 2004;74:533–538.
16. Iijima M, Brantley WA, Yuasa T, Kawashima I, Mizoguchi I. Joining characteristics of beta-titanium wires with electrical resistance welding. *J Biomed Mater Res B Appl Biomater*. 2008;85:378–384.
17. Baba N, Watanabe I. Penetration depth into dental casting alloys by Nd:YAG laser. *J Biomed Mater Res*. 2005;72B:64–68.
18. Suzuki Y, Ohkubo C, Abe M, Hosoi T. Titanium removable partial denture clasp repair using laser welding: a clinical report. *J Prosthet Dent*. 2004;91:418–420.
19. Baba N, Watanabe I, Tanaka Y, Hisatsune K, Atsuta M. Joint properties of cast Fe-Pt magnetic alloy laser-welded to Co-Cr alloy. *Dent Mater J*. 2005;24:550–554.
20. Watanabe I, Nguyen K, Benson PA, Tanaka Y. Joint properties of cast Fe-Pt magnetic alloy laser-welded to Au- and Ag- alloys. *J Biomed Mater Res*. 2006;76B:190–195.
21. Iijima M, Brantley WA, Yuasa T, Mugumuma T, Kawashima I, Mizoguchi I. Joining characteristics of orthodontic wires with laser welding. *J Biomed Mater Res*. 2008;84B:147–153.
22. Sevilla P, Martorell F, Libenson C, Planell JA, Gil FJ. Laser welding of NiTi orthodontic archwires for selective force application. *J Mater Sci Mater Med*. 2008;19:525–529.
23. Bock JJ, Bailly J, Fuhrmann RA. Effects of different brazing and welding methods on the fracture load of various orthodontic joining configurations. *J Orthod*. 2009;36:78–84.