Joining characteristics of titanium-based orthodontic wires connected by laser and electrical welding methods

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Abstract

This study investigated the possibility of electrical and laser welding to connect titanium-based alloy (beta-titanium and nickel-titanium) wires and stainless-steel or cobalt-chromium alloy wires for fabrication of combination arch-wires.Four kinds of straight orthodontic rectangular wires (0.017 x 0.025inch) were used: stainless-steel (S-S), cobalt-chromium (Co-Cr), beta-titanium alloy (β-Ti), and nickel-titanium (Ni-Ti). Homogeneous and heterogeneous end-to-end joints (15 mm long each) were made by electrical welding and laser welding. Non-welded wires (30 mm long) were also used as a control. Maximum loads at fracture (N) and elongation (%) were measured by conducting tensile test. The data (n=10) were statistically analyzed using analysis of variance/Tukey test ($P<0.05$).The S-S/S-S and Co-Cr/Co-Cr specimens showed significantly higher values of the maximum load (ML) at fracture and elongation (EL) than those of the Ni-Ti/Ni-Ti and β-Ti/β-Ti specimens for electrical welding and those of the S-S/S-S and Co-Cr/Co-Cr specimens welded by laser. On the other hand, the laser-welded Ni-Ti/Ni-Ti and β-Ti/β-Ti specimens exhibited higher values of the ML and EL compared to those of the corresponding specimens welded by electrical method. In the heterogeneously welded combinations, the electrically welded Ni-Ti/S-S, β-Ti/S-S and β-Ti/Co-Cr specimens showed significantly ($P<.05$) higher ML and EL than those of the corresponding specimens welded by laser. Electrical welding exhibited the higher values of maximum load at fracture and elongation for heterogeneously welded combinations than laser-welding.

Keywords: Titanium;Base-metal, Alloy wires; Electrical welding; Laser welding

1 Introduction

Commonly used orthodontic wires utilized stainless-steel, cobalt-chromium and beta-titanium and nickel-titanium alloys [1, 2]. Stainless-steel and cobalt-chromium alloy wires have been favorably used in orthodontics for more than a half century because of their low cost and excellent formability along with good mechanical properties such as high flexural strength and high modulus of elasticity [3, 4]. Although both stainless-steel and cobalt-chromium wires have similar elastic moduli [4], the yield strengths of cobalt-chromium alloy wires are relatively lower than those of stainless-steel alloy wires [2]. The cobalt-chromium alloy wires can be therefore heat-treated to achieve considerable increases in strength and resilience after they are easily manipulated into desired shapes due to their relatively low yield strength [5]. For both of these alloy wires, conventional soldering is conducted to fabricate the complex orthodontic appliances with a gas-torch and the use of solder and flux [6, 7].Nickel-titanium alloy wire have the properties of super-elasticity and shape memorial effect which is associated with the reversible transformation between austenitic and martensitic nickel-titanium [8]. The nickel-titanium alloy wires offer the modulus of elasticity approximately 20% that of the stainless steel alloy wires and have very wide elastic working range [8]. Therefore, they produce an optimum combination of light force and excellent spring-back for ideal tooth movement. Beta-titanium alloy wires show the modulus of elasticity approximately 40% that of the stainless steel alloy wires [3, 9]. Regardless of the lower values of yield strength, they have significantly improved values of spring-backbecause of the much lower value of elastic modulus. The improved spring-back of the beta-titanium wires remarkably increase their working range for tooth movement [9, 10]. Another important feature of this alloy wire is the absence of nickel, which is present in the former three alloy wires. Therefore, the beta-titanium wires are inevitably used for orthodontic patients who are allergic to nickel [11]. These titanium-based alloy wires, however, are difficult to join by conventional soldering since titanium has high affinity with oxygen at high temperature, resulting in the hard and brittle surface oxidized layers [12], which cause the weak joint with solder.

Since each alloy wire with different shape (round, oval, twist, square and rectangular) and different size offers different workability, the commercial combination arch-wires are currently available on the market. Those include prefabricated combination arch-wires made of stainless-steel, nickel-titanium or beta-titanium alloy with a rectangular anterior segment and a round posterior segment. The prefabricated combination arch-wires machined into one piecewithits desirable size on each segment.Another type of combination arch-wire is the compound retractionarch-wire, in which anterior segment uses a pre-torqued rectangular nickel-titanium wire and posterior segments are pre-torqued rectangular stainless-steel wires. The anterior and posterior segments are crimp-connected via crimping component.

If the titanium-based wires can be connected to stainless steel or cobalt-chromium wires by conventional dental soldering techniques, it increases the treatment options because the combination arch-wires mentioned abovecan be custom-fabricated in dental laboratory. Welding is well known technique for joining orthodontic wires and several studies have been carried out on the use of for welding dental metals [13-20]. Conceivable methods joining titanium-based alloys are electrical welding, infrared welding or laser welding. In the infrared welding, however, infrared ray can’t be concentrated on the small area of the wire’s joint and acts as agas torch flame [13]. As the results, the wide area from the wire join is affected by heat generated from infrared ray and oxidized in large amount. The heat-affected area can be minimized by the electrical welding [distance between two electrodes: 2 – 6 mm (1 – 3 mm from the joint)] [14, 15] and laser welding (beam stop diameter: 0.2 – 2.0 mm) [13]. The laser welding is suitable for joining of titanium-based alloys since titanium has low thermal conductivity and high laser beam absorption [16]: these tendencies are common for base metal alloys such as stainless-steel and cobalt-chromium alloys. Even the laser welding can weld the different types of dental alloys with different melting points [17-20]. In the electrical welding, the difference in electrical resistivity between titanium-based alloys and stainless-steel or cobalt-chromium alloys generates the heat which may be able to melt the dental solders on the joint under argon shielding.

Therefore, the objective of this study was to investigate the possibility of electrical and laser welding to connect titanium-based alloy (beta-titanium and nickel-titanium) wires and stainless-steel or cobalt-chromium alloy wires for fabrication of combination arch-wires and to evaluate the joint strengths of connected alloy wires in tensile mode.

2 Materials and Methods

2.1 Materials used

Four types of rectangular wire (0.017 inch × 0.025 inch) were used in this study: Nickel-Titanium (Ni-Ti,Nickel Titanium Straight Lengths,G&H Wire Company,Franklin,IN); Beta-Titanium (β-Ti, Beta Titanium wires,American Orthodontics, Sheboygan, WI); Stainless Steel (S-S, Stainless Steel Wire, American Orthodontics); and Cobalt-Chromium (Co-Cr,Chromium Cobalt Edgewise Wire,American Orthodontics).The elemental compositions of the wires are show in Table 1.

2.2 Preparation of welded wire specimens

The 15-mm-long wires were cut from each type of straight wire using a flat cutter (Flat cutter, TASK INC, Tokyo, JAPAN). 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). In electrical welding, the abutted specimens were soldered with a piece (0.005g) of gold solder (Degulor Lot2, DeguDent GmbH, Hanau, Germany; Au:73%, Pt:1.9%, Ag:10%, Cu:3%, Zn:3%) using an electrical welding machine (Model 2000, AWS/Lincoln Electric, Cleveland, OH) under argon gas shielding. The conditions for electrical welding were fixed at a current of 9A and a voltage of 1.2V. Two electrodes were placed on the topsurface (0.025-inch surface) of each side of wire (1.5mm apart from the abutted joint). Homogeneous end-to-end joint specimens were prepared for each type of wire, and heterogeneous end-to-end joint specimens were made in combination with Ni-Ti/S-S, Ni-Ti/Co-Cr, β-Ti/S-S, and β-Ti/Co-Cr. In laser welding, the abutted specimens were laser welded using a dental laser-welding machine

(Neo-Laser L, Girrbach Co, Pforzheim, Germany) under argon gas shielding. The pulse duration and output voltage for laser welding were fixed at 5 ms and 150 V, respectively. Four-point welding method was used, ie, one point on each 0.025-inch surface and two points wereadded on each 0.017-inch surface. 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. These conditions for laser welding were selected because the laser could penetrate into two-third of the thickness from each surface. Non-welded control wires (30 mm long) were also prepared for each type of wire.

2.3 Tensile test

Tensile test was conducted using a universal testing machine (5566S Testing systems, Instron Ind., Norwood, MA) at a cross-head speed of 1.0 mm/min. The gauge length was 10 mm (grips were located on the 5mm sides from the welded join). Maximum load at fracture (N) and total elongation (%) were measured for each combination (n=10) of homogeneously and heterogeneously welded groups. A statistical analysis was performed using the PASW Statistics (IBM, Armonk, NY). Since the data (n= 10) for the homogeneously welded were normally distributed, values were compared using one-way analysis of variance followed by Tukey test ($P<0.05$). The data for the heterogeneously welded combination were statistically analyzed using student T-test ($P<0.05$).

3 Results

The maximum load at fracture (N) and elongation (%) of the control group and homogeneously welded groups are presented in Figure 2. For control group, the highest maximum load at fracture was obtained for stainless steel wire followed by cobalt-chromium, nickel-titanium and β-titanium (significant each other at $p<0.05$). When the electrical welding was used for homogeneous welding, the S-S/S-S and Co-Cr/Co-Cr specimens showed significantly higher values of the maximum load at fracture and elongation than those of the Ni-Ti/Ni-Ti and β-Ti/β-Ti specimens and those of the S-S/S-S and Co-Cr/Co-Cr specimens welded by laser. On the other hand, the laser-welded Ni-Ti/Ni-Ti and β-Ti/b-Ti specimens exhibited higher values of the maximum load at fracture and elongation compared to those of the corresponding specimens welded by electrical method. Particularly, the elongation of the laser-welded Ni-Ti/Ni-Ti was extremely high when compared with the other welded groups.

The results of tensile test for heterogeneously welded combinations between Ti-based alloy wires and S-S or Co-Cr alloy wires were shown in Figure 3. In the heterogeneously welded combinations, the electrically welded Ni-Ti/S-S, β-Ti/S-S and β-Ti/Co-Cr specimens showed significantly ($P<.05$) higher maximum loads at fracture and elongations than those of the corresponding specimens welded by laser. There was no significant difference in maximum load at fracture for the Ni-Ti/Co-Cr combination between electrical welding and laser welding. However, the electrical welded Ni-Ti/Co-Cr specimens showed significantly higher elongation than that of the laser-welded Ni-Ti/Co-Cr specimens. The lowest maximum load at fracture for heterogeneously welded combinations was obtained for the laser-welded Ni-Ti/SS group.

4 Discussion

When the electrical welding and laser welding are compared in the homogeneously welded combinations (Fig. 2), titanium-based alloy wires (Ni-Ti and β-Ti) welded by laser exhibited higher maximum loads at fracture and elongation than those of the corresponding combinations welded by electrical method. On the other hand, the S-S and Co-Cr alloy wires showed high maximum loads at fracture and high elongation when the electrical welding was conducted. These results could be obtained because laser welding is suitable method to join the titanium based alloys rather than the S-S and Co-Cr alloys. Note that the titanium have higher laser beam absorption and lower thermal conductivity compared to Fe, Ni, Cr and Co contained in the S-S and Co-Cr alloys. Another reason might be that the gold solder in electrical welding possess higher affinity with S-S and Co-Cr alloys than with titanium based alloys. One of the interesting results obtained in Fig. 2 was that the homogeneously laser-welded β-Ti wires showed maximum load at fracture equivalent to that of the control β-Ti wires and higher than those of laser-welded S-S and Co-Cr wires.

In the level of phase structure it is already concluded by other groups studies that, welded shape memory alloys fracture behavior shows significant reduce of tensile strength which is caused mainly by formation of Ti_2Ni precipitations along the grain boundaries. Also it is well known that in principal Ti_2Ni formation can be reduced by increasing the cooling rate which is higher in Laser welding compare to other welding methods especially the electrical welding [21]. In Figure 2 the result for maximum load at fracture for electrical and laser welding methods of Ni-Ti shows lower than β-Ti which can be because of Ti_2Ni in the weld. Control S-S and Co-Cr alloys have high mechanical properties because of them microstructure and crystals arrangement which are very sensitive against heating or annealing. Welding and heat affected zone (HAZ) will decrease hardness and strength of these alloys significantly and beside that in laser welded samples crystal structure cannot be formed and rearranged properly because of very high cooling rate therefore the welded samples by laser for S-S and Co-Cr shows less maximum load fracture compare to electrical welding.

Our previous study[18] conducted by flexural three-point bending test indicated that the deflection loads (at 3.0 mm deflection) of thecontrol β-Ti alloy wires were greater than those of the control Ni-Ti alloy wires and about two third of the deflection loads for the control S-S and Co-Cr alloy wires. And, the mean deflection load of the laser-welded β-Ti alloy was half of the controlβ-Ti and between those of the homogeneously laser-welded S-S and Co-Cr alloy wires. In this study using tensile test to investigate the welding strengths of orthodontic wires, the control β-Ti alloy wires had a mean maximum load at fracture lower than that of the control Ni-Ti alloy wires and was approximately half of the control S-S and Co-Cr alloy wires. The highest value of mean maximum load at fracture for the laser-welded β-Ti wires could be obtained due to the difference in test mode (tension mode vs. bending mode) and super-elasticity of the Ni-Ti alloy wires. Note that the value of elongation for control Ni-Ti group was extremely high (approx. 25%) and even laser-welded Ni-Ti wires showed very high value (15%) of elongation owing to their super-elasticity.

In the heterogeneously welded combinations (Fig. 3), all of the electrically welded combinations, except for the Ni-Ti/Co-Cr combination in which the maximum loads at fracture are similar between both welding methods, demonstrated the higher mean maximum loads at fracture than those of the corresponding combinations welded by laser. In regard to the elongation, the electrical welded combinations had significantly higher values (more than 1.5%) than the laser-welded combinations (less than 1.0%). These results indicated that the electrical welding is suitable for heterogeneously welded combinations between titanium based alloy wires and S-S or Co-Cr alloy wires. The lowest mean maximum load at fracture and elongation was obtained for the laser-welded Ni-Ti/S-S. In case of welding of β-Ti to the different alloys such as S-S and Co-Cr as a source of Ni element some intermetallic phases will be formed base on the binary phase diagram and other groups published articles. In the laser welding of Ti to the alloys which are containing Ni such as; S-S and Co-Cr layers of Ni_3Ti, Ni_3Ti+NiTi eutectic, Ni-Ti dendrites and Ti_2Ni constitute the microstructure in the middle of the weld can be formed [22, 23]. In fig. 3 all conditions shows 2 or 3 times less maximum load at fracture compare to control samples. The reason for that can be the fact, which was explained in the beginning of the paragraph. Finally according to the results the welding method suppose to be selected by paying attention to different parameters such as; kind of alloy, phase structure of alloy, effect of heating on phase transformations and effect of cooling rare on the alloy structure.

This result is in agreement with the results obtained for the lowest deflection load for the laser-welded Ni-Ti/S-S in the previous study using a three-point bending test. [18] Therefore, it could be stated that the affinity between nickel titanium (Ni-Ti) and stainless steel (S-S) is very weak when laser welding is applied for connecting of these alloy wires.

When both modes of electrical and laser welding are compared for heterogeneous combinations, the joint by laser welding is completely melted by laser and is composed of intermetallic compound with the elements contained in heterogeneous alloys, whereas, the joint by electrical welding is not melted but is covered with melted gold solder. Therefore, the joint strength of electrical welding could be the strength of solder itself, whereas, the strength of laser-welded joint is the real strength of welded joint of intermetallic compound. The increase of the amount of solder might result in increase of joint strength for electrical welding. Even so, the values of maximum loads at fracture were more than 80N (approx. 8kgf) when the electrical welding was applied for any of heterogeneous alloy wire combinations. This value would be enough amount of force to move teeth in orthodontic treatment. However, torsion properties of connected wires should be investigated before clinical application of the custom fabricated combination arch-wires.

5 Conclusion

In homogeneous welding, laser welding indicated high value of maximum load at fracture and elongation for welding of titanium based alloy wires, whereas the S-S and Co-Cr alloy wires showed high load values when electrical welding was used. Electrical welding exhibited the higher values of maximum load at fracture and elongation for heterogeneously welded combinations than laser-welding.

Acknowledgments
This study was partially supported by a grant MEXT KAKENHI Grant Number 23659905.

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Figure captions:

Fig. 1 A custom-made jig for the welding of orthodontic wires.

Fig. 2 The maximum load at fracture (N) and elongation (%) of control wires and homogeneously welded combinations (EW: electrical welding Laser: laser welding). ＊shows significant differences for maximum load at fracture ($p<0.05$) †shows significant differences for elongation ($p<0.05$).

Fig. 3 The maximum load at fracture (N) and elongation (%) of heterogeneously welded combinations (EW: electrical welding Laser: laser welding). ＊shows significant differences for maximum load at fracture ($p<0.05$) †shows significant differences for elongation ($p<0.05$).

Fig. 4 The welded specimens before and after tensile testing; (a) electrically welded Ni-Ti/S-S specimen, (b) electrically welded Ni-Ti/S-S specimen after tensile testing, (c) laser-welded Ni-Ti/S-S specimen, (d) laser-welded Ni-Ti/S-S specimen after tensile testing.

Table 1 Elemental composition (wt.%) for the wires*

	Fe	Co	Cr	Ni	Mn	Ti	Sn	Zr	Mo	Si
Ni-Ti				55		45				
Beta-Ti						74-82	3.8-5.3	4.5-7.5	10-13	
Stainless steel	72		17	8	2					1
Co-Cr	7-21	39-42	19-22	14-18	1-2.5				6.5-8	

* 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: Si, silicon.

Figure 1

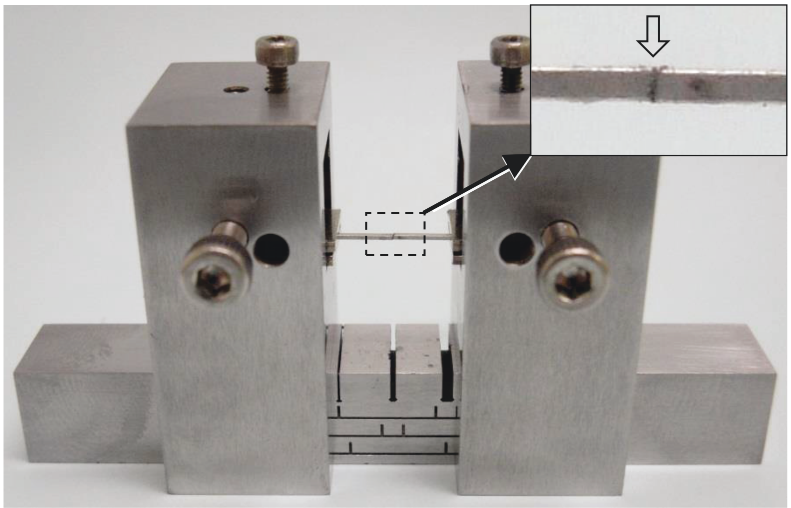
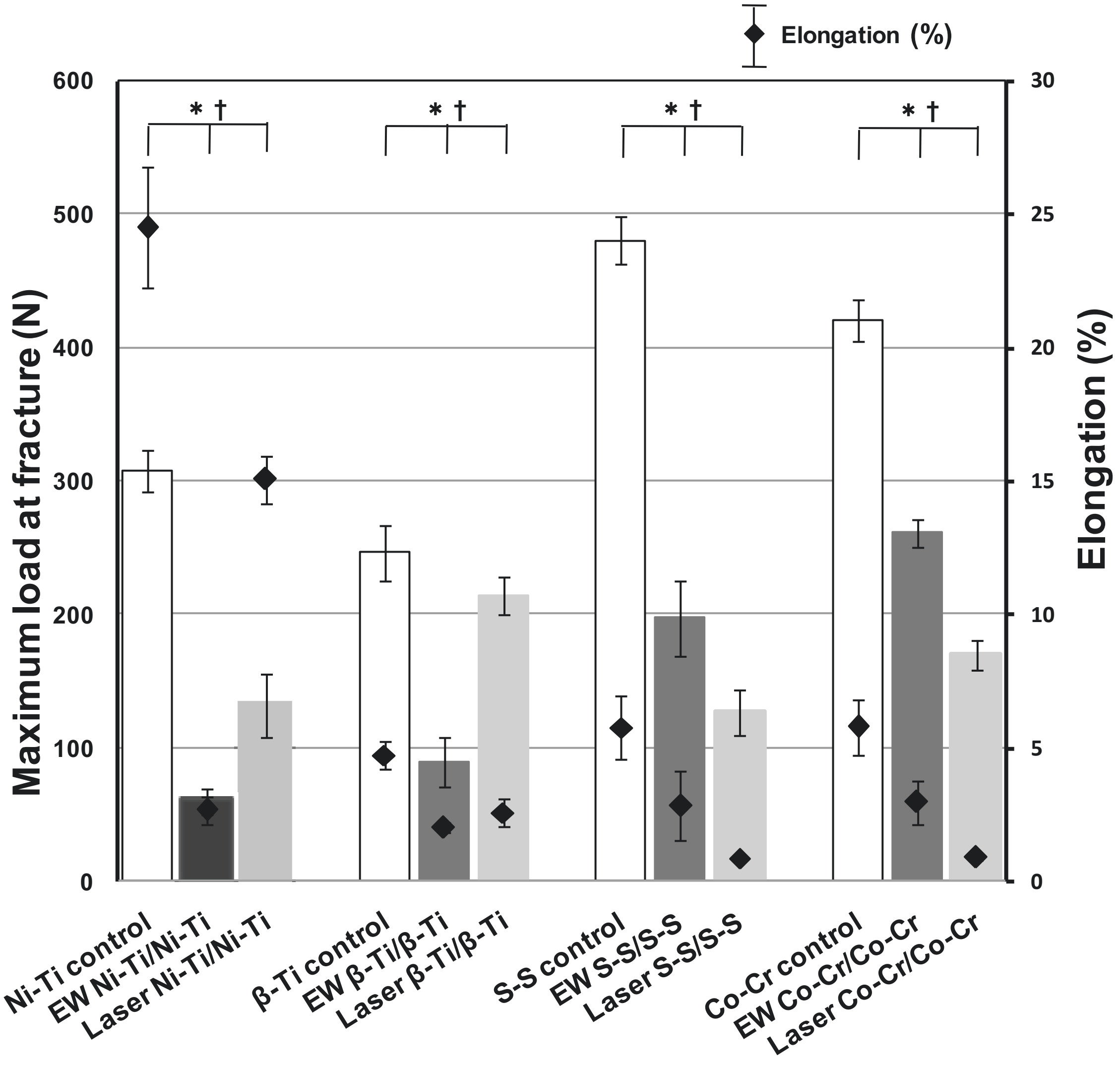
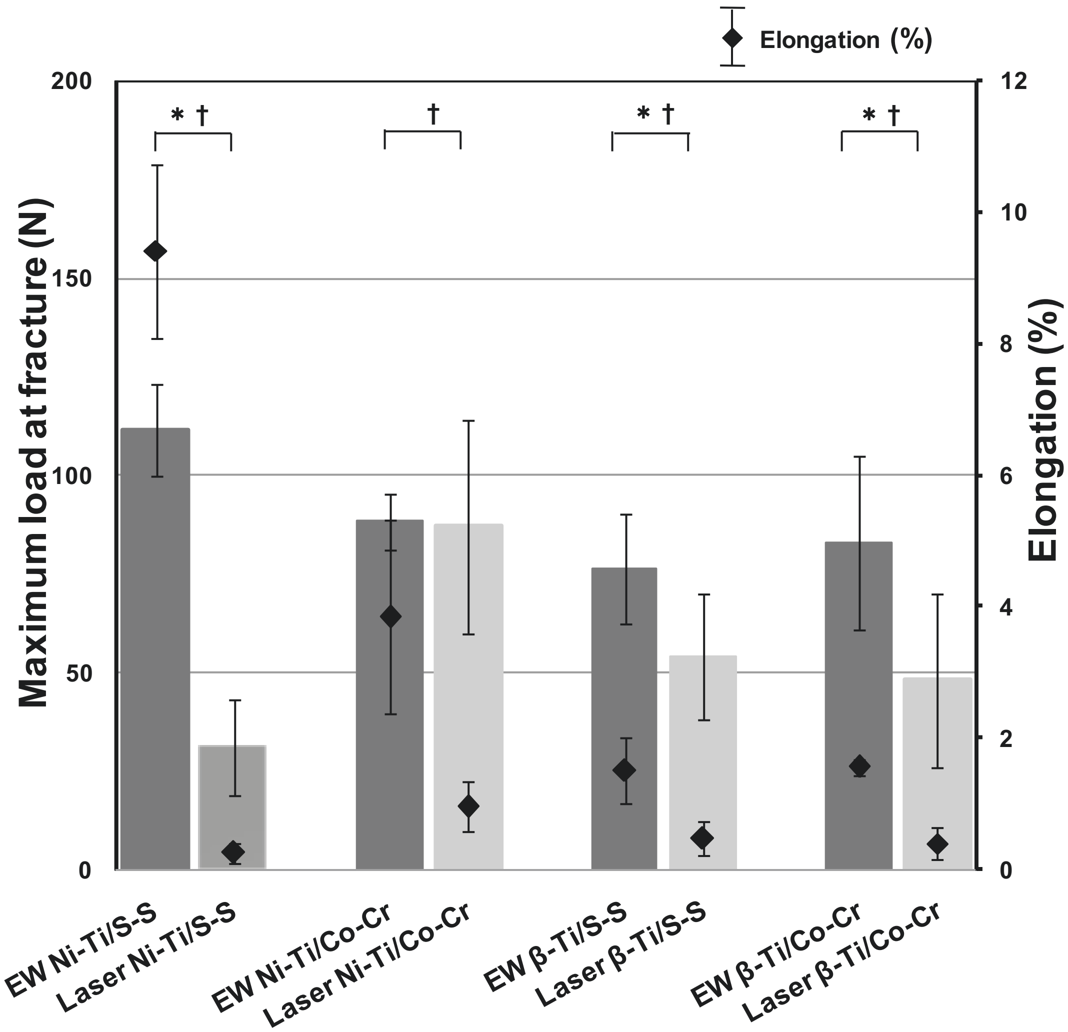


Figure 2



Elongation (%)
Maximum load at fracture (N)
Elongation (%)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
* †
* †
* †
* †
Ni-Ti control
EW Ni-Ti/Ni-Ti
Laser Ni-Ti/Ni-Ti
β-Ti control
EW β-Ti/β-Ti
Laser β-Ti/β-Ti
S-S control
EW S-S/S-S
Laser S-S/S-S
Co-Cr control
EW Co-Cr/Co-Cr
Laser Co-Cr/Co-Cr

Figure 3



Elongation (%)
Maximum load at fracture (N)
Elongation (%)
200
150
100
50
0
12
10
8
6
4
2
0
* †
†
* †
* †
EW Ni-Ti/S-S
Laser Ni-Ti/S-S
EW Ni-Ti/Co-Cr
Laser Ni-Ti/Co-Cr
EW β-Ti/S-S
Laser β-Ti/S-S
EW β-Ti/Co-Cr
Laser β-Ti/Co-Cr

Figure 4