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Bending properties of hollow super-elastic Ti–Ni alloy wires and compound wires with other wires inserted

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The purpose of this research was to investigate the possible orthodontic application of the hollow super-elastic Ti–Ni alloy wire, which was thought not only to deliver much lower and more continuous orthodontic force than conventional Ti–Ni wires, but also be able to be applied as a compound wire when combined with another wire. The examinations of bending properties were performed by the three-point bending test. The following results were obtained.

1. The hollow wire had lower load in the super-elastic range, smaller load-deflection rate and stress hysteresis in comparison with the conventional wire of the same diameter.
2. The load of the hollow wire was controllable by heat treatment. The stress hysteresis was further decreased by a two-step heat treatment.
3. The compound wire formed by inserting other types of wires into the hollow core exhibited changes in various bending properties such as increased load or load-deflection rate, according to the types and diameters of the inserted wire.

The hollow wire delivers much lighter and more continuous orthodontic force, and, through heat treatment or deployment as a compound wire, it is possible to alter various bending properties. Therefore, this hollow wire was evaluated as a promising candidate for orthodontic application.

1. Introduction

Super-elastic Ti–Ni alloy wire is widely used in clinical orthodontic treatment [1, 2]. Some heat treatment methods have been used to control orthodontic force delivered from super-elastic Ti–Ni alloy orthodontic wire. Previous studies have examined properties such as the load of the super-elastic range (hereinafter called ''load level''), as well as the methodology of heat treatment [3–6]. Our research, on the other hand, focuses on the incorporation of a hollow cross-section in the wire as a new method for changing the properties of the super-elastic Ti–Ni alloy wire.

Currently, hollow super-elastic Ti–Ni alloy wire is produced for the application of medical catheter tubing. This type of hollow wire has the potential advantages of delivering significantly lighter and more continuous orthodontic force than do conventional orthodontic wires, and of customization of bending properties by heat treatment or insertion of another wire into the hollow core. Therefore, the purpose of this research was to investigate the potential for orthodontic application of the hollow super-elastic Ti–Ni alloy wire (hereinafter called ''hollow wire''). These experiments compared the bending properties with those of the conventional super-elastic Ti–Ni alloy wire, and examined the changes induced by heat treatment or formation of compound wire using other types of wire in the hollow core.

2. Materials and experimental procedures

2.1. Bending properties of hollow wire

Hollow wires of 0.508 mm (0.020 inch) outer diameter with 0.388 mm (0.0153 inch) inner diameter (Fig. 1), manufactured by Furukawa Electric Co., Ltd., were used

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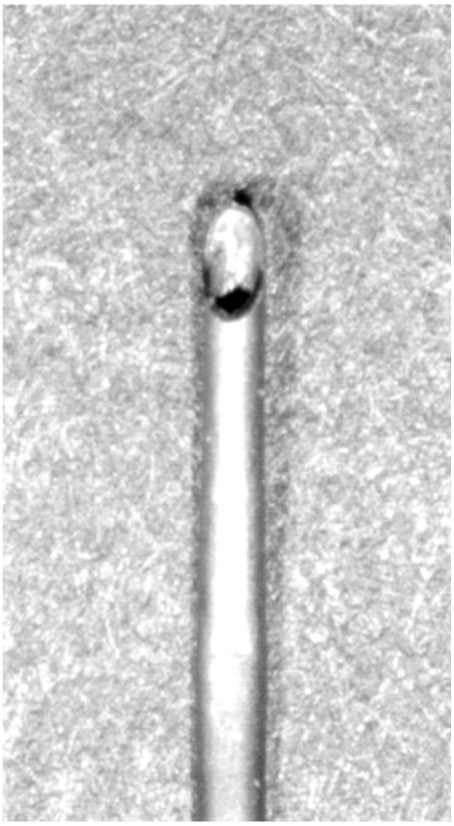


Figure 1 The hollow super-elastic Ti-Ni alloy wire used in this study.

as the ''original hollow wires'' after heat treatment at 500 °C for 20 min. For comparison, super-elastic Ti–Ni alloy round wires with a diameter of 0.020 in (Sentalloy Light, Tomy International Inc., Japan), were used as the ''conventional-TN''. The alloy organizations are Ti–50.85Ni (mol %) in all of them.

Assessment of bending properties of specimens was derived from the load-deflection curve obtained from the three-point bending test [2, 5 ,7] in a 37 °C environment. The wire was deflected by 2 mm, and then the load reduced to 0 gf.

Fig. 2 shows the parameters that were used for the evaluation of the bending properties. The SE-point load is the load at 1 mm deflection in the unloading process. Stress hysteresis is defined as the difference in load between the SE-point load and the load at 1 mm deflection under increasing deflection. Load-deflection rate is defined as the inclination of the elastic loading range [8].

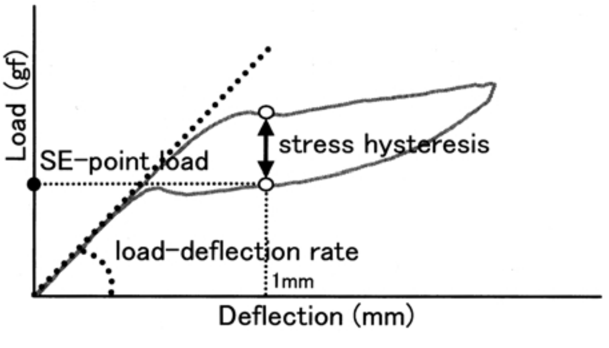


Figure 2 Schematic load-deflection curve of the super-elastic Ti-Ni alloy wire in three-point bending test with applied parameters.

2.2. Changes in the bending properties of hollow wire by heat treatment

A bath of nitrate salt was used for the heat treatment as described in the reports on the conditions for medium temperature heat treatment [3–5]. Five conditions of temperature (400, 450, 500, 550, 600 °C) and four conditions of time (5, 30, 60, 120 min) were combined for total of 20 conditions. Also, to evaluate the advantageous effect of decreasing stress hysteresis, we carried out a two-step heat treatment [6]: 600 °C for 5 min (primary heat treatment) and 280 °C for 180 min (secondary heat treatment). Water-cooling was applied immediately after heat treatment was performed, on each specimen. The bending properties were examined by parameters similar to those described above.

2.3. Bending properties of compound wire

Three types of compound wires were made by inserting Co-Cr alloy or super-elastic Ti-Ni alloy wire into the core of the original hollow wire. The Co-Cr alloy wires had diameters of 0.010 and 0.012 inch (Rocky-mountain Morita Co., Japan), while the super-elastic Ti-Ni alloy wire had a diameter of 0.014 inch (Sentalloy Heavy, Tomy International Inc., Japan). The evaluation of the bending properties was derived from the load-deflection curve obtained from the three-point bending test.

3. Results

3.1. Bending properties of the hollow wire

Fig. 3 shows the load-deflection curves of the original hollow wire and the conventional-TN, as obtained from the three-point bending test. In both specimens the load was constant over a certain range of deflection, despite the difference in the deflection magnitude that exhibited super-elasticity. The SE-point load of the conventional-TN was 110 gf, while that of the original hollow wire was 80 gf. Stress hysteresis of the conventional-TN was 168 gf, while that of the original hollow wire was only 67 gf. Load-deflection rate of the conventional-TN was 400 gf/mm, and that of the original hollow wire was 210 gf/mm, about a half of the former.

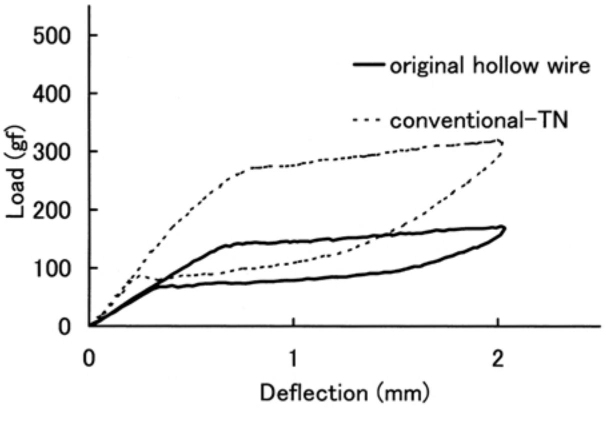
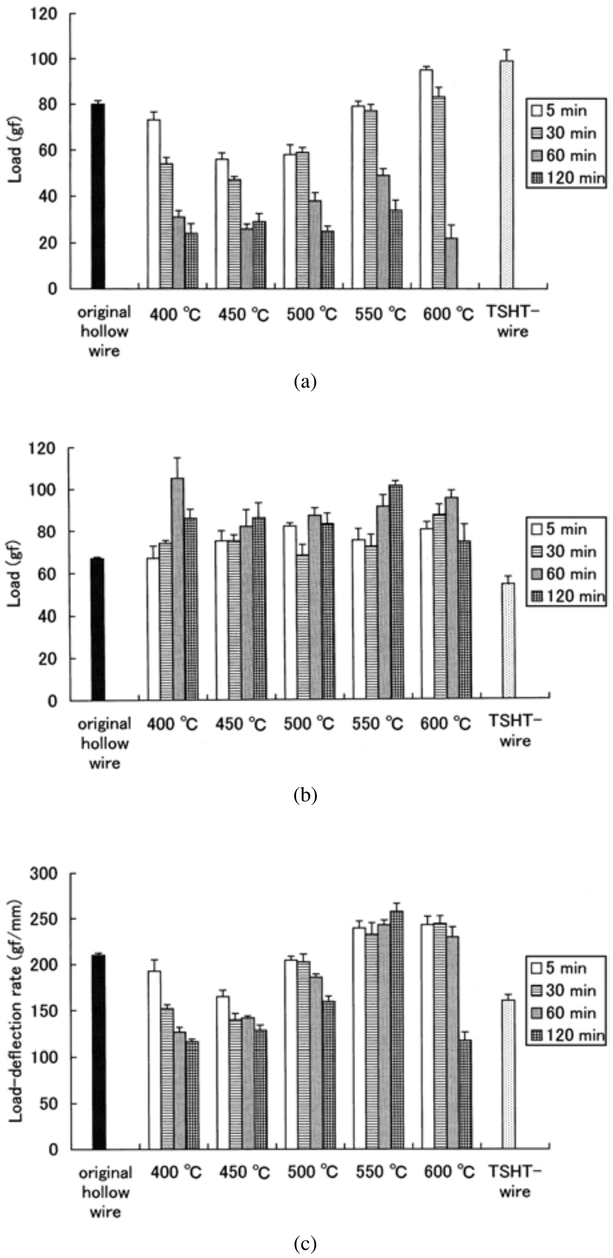


Figure 3 Comparison of load-deflection curves in three-point bending test between original hollow wire and conventional-TN.

3.2. Changes in the bending properties of hollow wire by heat treatment

Fig. 4(a)–(c) show the comparisons of three parameters obtained from the three-point bending test. The SE-point load decreased as the heat treatment period increased in all heat-treatment temperature conditions (Fig. 4(a)). Also, with same heat-treatment period conditions, the load for the 450 °C group was the lowest except 120 min treatment. While the SE-point load increased from the original hollow wire at 600 °C with short-period heat treatment, a decrease of the SE-point load was observed at 600 °C with long-period heat treatment (over 60 min), due to an increase of residual deflection.

Stress hysteresis values were greater than 67 gf of the original hollow wire under most conditions of heat treatment (Fig. 4(b)). As for the load-deflection rate, the value decreased from the 210 gf/mm of the original hollow wire to 140–200 gf/mm for a heat treatment using a lower temperature (below 500 °C), but increased to 230–245 gf/mm for a heat treatment using a temperature higher than 550 °C (Fig. 4(c)).



(a)

(b)

(c)

Figure 4 Change of parameters by heat treatment. (a) SE-point load; (b) stress hysteresis; (c) load-deflection rate.

On the other hand, when the two-step heat treatment was performed (referred to as ''TSHT-wire''), the SE-point load increased by 19 gf, and load-deflection rate decreased by 50 gf/mm, compared with original hollow wire (Fig. 4(a)–(c)). Also, stress hysteresis was only 54 gf, the smallest value among all specimens with heat treatment, and a 13 gf decrease from that of the original hollow wire (Fig. 4(b)).

3.3. Bending properties of compound wire

Fig. 5 shows the load-deflection curves of the compound wires. Elastic transformation of the compound wires inserted with Co–Cr alloy wire of 0.010 or 0.012 inch diameter (referred to as ''compound-10'', and ''compound-12'') was seen up to a deflection of 0.6 mm; afterward, the inclination of the curve became slightly smaller and then further decreased. At the phase of unloading, the curve changed gradually to a deflection of 0.3 mm, after which a direct decrease of load was seen, but residual deflection was not observed. The SE-point loads of compound-10, compound-12, and the original hollow wire were 125 gf, 215 gf, and 80 gf, respectively. Load-deflection rate was 270 gf/mm, 330 gf/mm, and 210 gf/mm, respectively.

When the same alloy as used in the super-elastic Ti–Ni alloy wire was inserted (compound-TN), the super-elasticity was similar to that of the conventional super-elastic Ti–Ni alloy wire with no residual deflection, although the inclination was more changeable. Compared with the original hollow wire, SE-point load, load-deflection rate, and stress hysteresis changed from 80 gf to 172 gf, 210 gf/mm to 300 gf/mm, and 67 gf to 80 gf, respectively.

4. Discussion

4.1. Influence of the hollow cross-section on the bending properties

Wires made of the same material share the same modulus of elasticity regardless of their shape. Therefore, the bending properties are fundamentally influenced by the moment of inertia, which differs according to wire cross-section [8, 9]. The moment of inertia of the conventional

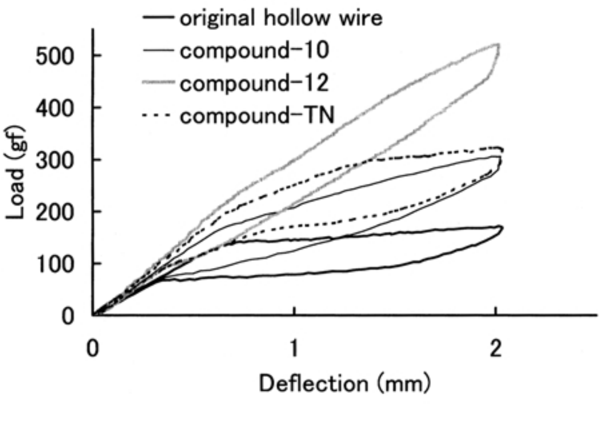


Figure 5 Comparison of load-deflection curves of compound wires.

round wire (I) and the hollow wire (I') can be calculated by the following formulae [10].

$$I = d_0^4 \pi/64 \qquad I' = (d_0^4 - d_1^4)\,\pi/64$$

where d_0 diameter, and d_1 inner diameter.

If the moment of inertia of the wires used in this study are calculated from these formulae, then I (where diameter is 0.508 mm) becomes $3.27 \times 10^{-3}\,\mathrm{mm}^4$ and I' (where diameter is 0.508 mm and inner diameter is 0.388 mm) becomes $2.15 \times 10^{-3}\,\mathrm{mm}^4$. Since the moment of inertia of hollow wire is equal to about 65% of the conventional round wire, it is speculated that the changes in the bending properties of hollow wire should be about 65% of those of conventional round wire. However, the results obtained showed changes from conventional round wire to hollow wire of 72% in SE-point load, 50% in load-deflection rate, and 40% in stress hysteresis.

Load-deflection rate, one of the parameters that determine the elastic property, is not significantly changed by heat treatment [9]; therefore, it was largely influenced by the decrease in the moment of inertia. On the other hand, the changes in SE-point load and stress hysteresis, the parameters concerned with the super-elastic range, were influenced by martensitic transformation behavior such as heat treatment history. Although these were influenced by the change in the moment of inertia to some degree, it appeared not to be the sole factor on the bending properties.

4.2. Changes of the bending properties of hollow wire by heat treatment

Ti-Ni alloys are known to change their properties substantially after heat treatment [4]. In this study, we have examined the changes in the bending properties with the heat-treatment condition set at the medium temperature range of 400–550 °C, as this is reported to bring excellent mechanical properties for orthodontic super-elastic Ti-Ni alloy wires [4]. The earlier studies indicated that a heat treatment temperature below 450 °C does not affect the bending properties, while a temperature above 550 °C causes deterioration of super-elasticity, giving rise to plastic deformation [6]. As for the results of this study, while fine super-elasticity was obtained in a short-period heat treatment at 550 and 600 °C, heat treatment at 600 °C for 120 min caused a sharp decrease in load level and load-deflection rate. Because the transformation temperatures rose as a result of heat treatment and this temperature exceeded the environmental temperature, the load level is thought to have been decreased, resulting in apparent plastic deformation.

In this study, the increase in stress hysteresis associated with the decrease in load level was obtained by performing heat treatment in the medium temperature range of 400–550 °C. It has been assumed that the stress hysteresis of the super-elastic Ti-Ni alloy wire influenced the alteration of the orthodontic force in the presence of temperature changes in oral environment. By maximally suppressing this stress hysteresis, it was suggested that more stable and continuous orthodontic forces could be delivered in the oral environment [6].

Former studies reported that changing the transformation behavior to decrease the stress hysteresis of the super-elastic Ti-Ni alloy wire was effective especially when the R-phase transformation was involved [11, 12]. To obtain the transformation behavior that appears in the R-phase, application of a two-step heat treatment [6] and addition of a third element [13] has been explored. Thereupon, in this research, a two-step heat treatment was selected and performed at 600 °C for 5 min and at 280 °C for 180 min on hollow wires, resulting in a 13 gf decrease in stress hysteresis from the original hollow wire. While stress hysteresis of the original hollow wire was already only 40% of that of the conventional-TN, an additional decrease was obtained by performing this two-step heat treatment. Since the SE-point load increased by this treatment, the decrease in stress hysteresis was very effective to improve the bending properties. As found in former studies, two-step heat treatment for the hollow wire further decreased its stress hysteresis.

The hollow wire has much smaller stress hysteresis in comparison with the conventional wire partially because of the reduction of cross-section, and further by the application of the two-step heat treatment, so that the load change by the oral temperature becomes very small. Therefore, if this hollow wire were to be used in clinical orthodontic treatment, tooth movement by much lighter and more stable orthodontic force would be applicable.

4.3. Bending properties of the compound wire

In clinical orthodontics, it is frequently necessary to simultaneously provide tooth movement by super-elasticity and fixation of the anchorage unit, utilizing high load-deflection rate, in the same arch wire. Until now, the control of the orthodontic force delivered from the super-elastic Ti-Ni alloy wire has been controlled by using the direct electric resistance heat treatment (DERHT) method [14]. Alternatively, with a hollow wire, it would be possible to change the orthodontic force by inserting different wires into the hollow core, with the DERHT method still remaining available. Hence, the present investigation was carried out to determine the bending properties of compound wires formed by inclusion of either Co-Cr alloy or super-elastic Ti-Ni alloy wires. The results showed that when different diameters of Co-Cr alloy wire were inserted, the load-deflection rate increased with diameter. And, the load-deflection curve lost its super-elasticity as soon as the inclination of the super-elastic range underwent a transition, changing smoothly from the unique hysteresis curve of the super-elastic Ti-Ni alloy wire into a curve representative of the Co-Cr alloy wire. The load delivered from the compound wire of Co-Cr alloy is equal to the sum of the load that is delivered from both components, inner and outer. Therefore, it is possible to control the load-deflection rate of the compound wire with Co-Cr alloy wire insertion, partially by changing the diameter of the inserted wire.

On the other hand, with the super-elastic Ti-Ni alloy wire inserted into the hollow wire, it is possible to control the super-elasticity partially and reversibly. In other words, it would become possible to select the load of the super-elastic range according to the stage of orthodontic treatment, by combining the types of inner and outer wires or by conditioning with heat treatment.

These findings revealed that the hollow super-elastic Ti-Ni alloy wire has better bending properties than a conventional round wire of the same material. Furthermore, it is possible to change the properties of the hollow wire by performing heat treatment and/or by forming it as a compound wire. Therefore, when applied to the field of clinical orthodontics, more efficient and more carefully regulated tooth movement should be possible.

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