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Anisotropic orthodontic force from the hollow super-elastic Ti-Ni alloy wire by transforming the wire cross-section

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The purpose of this research was to devise a method for transforming the cross-section of the hollow super-elastic Ti-Ni alloy round wire and to examine the changes in its bending properties for clinical orthodontic application. The specimen wires were pressed with the use of heated pliers to transform the cross-sectional shape. As a result, transformation of the wire cross-section with super-elasticity was possible. As a verified by cantilever test and three-point bending test of the transformed specimens, a two-dimensional orthodontic force, which was different in each bending direction, was obtained. The hollow wire showed considerably high load level in the long axis along with markedly low load level in the short axis, which was mainly caused by the change in the moment of inertia by transforming the cross-section. It was revealed that, by transforming the wire cross-section of the hollow super-elastic Ti-Ni alloy round wires, anisotropic orthodontic force in bending properties could be obtained with super-elasticity.

1. Introduction

Ti-Ni alloy wire shows super-elasticity providing light continuous force for efficient tooth movement, and has been used widely in clinical orthodontic treatment [1]. Previously, the authors examined the bending properties of the hollow super-elastic Ti-Ni alloy round wire (hereinafter called ‘‘hollow wire’’) in terms of its application to clinical orthodontics. The results showed that the hollow wire delivers much lighter and more continuous orthodontic force in comparison to conventional super-elastic Ti-Ni alloy round wires, and it was possible to change the bending property by heat treatment or by being compounded with another wire [2].

The cross-section of the hollow wire can be changed with comparative ease because of the existence of the hollow core in comparison with conventional wires. If it becomes possible to transform the hollow wire cross-section, the bending properties could be made dependent on direction. By using such anisotropic force to obtain tooth movement in a multi-bracket system, the orthodontic force is thought to be directionally dependent, in addition to providing super-elasticity.

The purpose of this research was to devise the transformation method for a hollow wire cross-section, and then to evaluate the changes in bending properties accompanied by the transformation of the cross-section.

2. Materials and methods

2.1. Materials

Two kinds of hollow wires (Furukawa Electric Co., Ltd., Japan) were used in different diameters but with the same thickness. One was 0.71 mm in outer diameter and 0.59 mm in inner diameter (71-59), and the other was 0.61 mm in outer diameter and 0.49 mm in inner diameter (61-49). The alloy composition was Ti–50.85Ni (mol %) in both types. An ‘‘original wire’’ was made by pre-heat treatment with use of a bath of nitrate to remove the influences of processing, which is to decrease the load of the super-elastic range (load level) and elastic load-deflection (L/D) rate, in order to facilitate the transformation of the wire cross-section with excellent super-elasticity. This pre-heat treatment condition was set at 500 °C for 60 min from the studies concerning heat treatment conditions of super-elastic Ti-Ni alloy wires [3].

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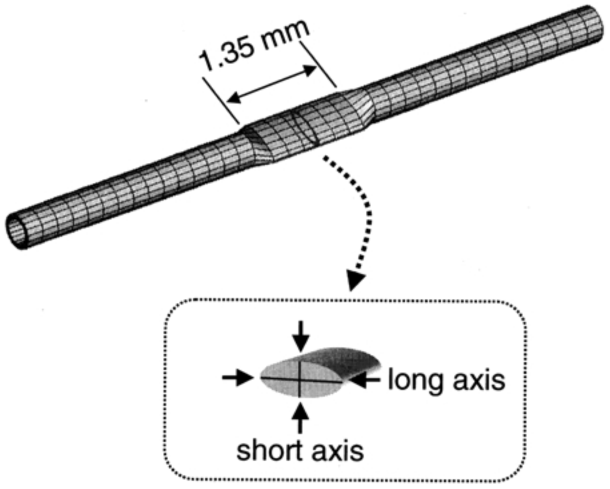

Figure 1 Schematic drawing of the transformation of the specimen.

2.2. Transformation of wire cross-section

Specimens were transformed by a direct-compression method with pliers heated by a torch. Therefore, the width of the transformed segment was equal to the width of the jaws of the pliers, which was 1.35 mm. Compression procedure was routinely performed for 5 s so as to transform the cross-section consistently. To monitor the heating temperature a CA thermocouple was used, and the transformation was performed immediately after the temperature of the jaws of the pliers reached 300 °C. The minimum and maximum diameters of the transformed segments (called the short axis and long axis, respectively as shown in Fig. 1) were measured with a micrometer.

2.3. Cantilever test

To evaluate the changes in bending properties by cross-sectional transformation, we made a cantilever bending test apparatus following the ADA specification [4], as shown in Fig. 2. The distance from the loading point on the specimen to the rotation axis was 12.0 mm. The center of the transformed segment was located at the center of this distance, 6.0 mm from the rotation axis. The specimen was restrained at the rotation axis but free at the loading point. The test was performed in two directions, parallel to the long axis and to the short axis. The original wire was also tested for comparison. Specimens were subjected to a deflection angle of 45°, then the load was reduced to 0 gf. Because the properties of Ti-Ni alloy are strongly influenced by environmental temperature, the test was carried out at 37 °C, the assumed oral temperature.

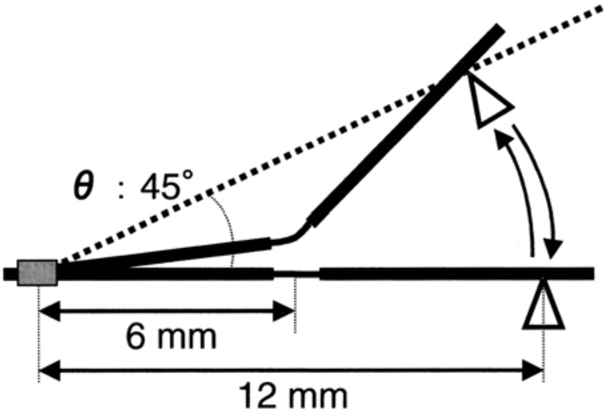

Figure 2 Schematic drawing of the cantilever test.

2.4. Three-point bending test

As shown in Fig. 3, based on the supposition that anisotropic force would be applied selectively to the tooth movement in a clinical orthodontic case, a three-point bending test [5–7] was also carried out. The inter-contact distance was 14 mm. The transformed segments were centrally located between the poles, and the load at the center pole was detected. Similar to the cantilever tests, specimens were tested in both the long axis and the short axis directions on the transformed segment, and the original wire was also tested. The specimen was deflected by 2.0 mm and then the load was reduced to 0 gf. This test was also carried out at 37 °C.

2.5. Statistics

In both the bending tests, two bending parameters were used to evaluate the bending property quantitatively. One was ''SE-point load'' showing the load in the super-elastic range at 22.5° or 1.0 mm deflection in the unloading process, and the other was ''elastic L/D rate'' showing the inclination in the elastic range [8]. One-way factorial analysis of variance was used for the detection of the difference among groups. The differences between long/short axis and original wires were detected by Dunnett's test as the *post hoc* test. Statistical significance was set at $p < 0.01$.

3. Results

3.1. Change of wire dimensions by transformation

As shown in Table I, for 71-59 wires, the diameter changed from 0.71 mm (original wire) to 1.06 (± 0.01 S.D.) mm in the long axis direction, and to 0.30 (± 0.03) mm in the short axis direction. For 61-49 wires, the diameter changed from 0.61 mm to 0.88 (± 0.03) mm and 0.33 (± 0.02) mm, respectively. Although these specimens had the same thickness, 71-59, with its larger hollow core, underwent greater changes than 61-49. The difference in specimen diameters under the same condition was small as

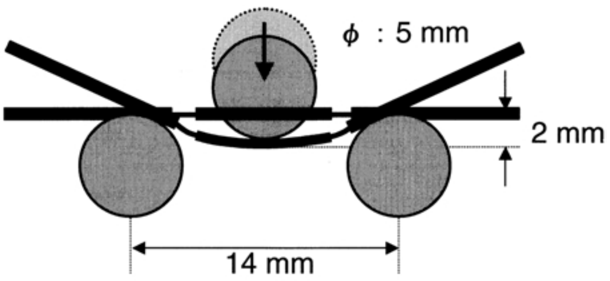

Figure 3 Schematic drawing of the three-point bending test.

TABLE I Outer dimension of the hollow wire by transformation (mm)

Code	Original wire	Long axis	Short axis
71-59	0.71	1.06 (0.01)	0.30 (0.03)
61-49	0.61	0.88 (0.03)	0.33 (0.02)

( ): S.D.

shown by the S.D. values, which suggested that the cross-sectional transformation was performed almost uniformly.

3.2. Cantilever bending property

Figs 4 and 5 show typical load-deflection curves for each specimen in the cantilever test. When the test direction was parallel to the long axis, the curve of the transformed wire differed only slightly from that of the original wire. In contrast, a significant decrease of load level and inclination of elastic range were seen in the direction parallel to the short axis. There was very small residual deflection after being unloaded, by which all specimens were evaluated to show good super-elasticity.

Fig. 6 shows the changes of the SE-point load at 22.5° deflection from the load-deflection curve of each specimen. Fig. 7 shows the changes of the elastic L/D rate. Although the change in SE-point load for the long axis was not large, that for the short axis of 71-59 decreased markedly from 41 gf (original wire) to 13 gf, while that of 61-49 decreased from 18 gf to 12 gf. Elastic L/D rate for the long axis of 71-59 changed from 67 gf degree (original wire) to 86 gf/degree, while that of 61-49 changed slightly from 49 gf/degree to 52 gf/degree. In contrast, the decrease for the short axis was large, 28 gf/degree for 71-59, 21 gf/degree for 61-49. There were statistically significant differences in SE-point load and elastic L/D rate from original wire in all conditions except the long axis of 61-49.

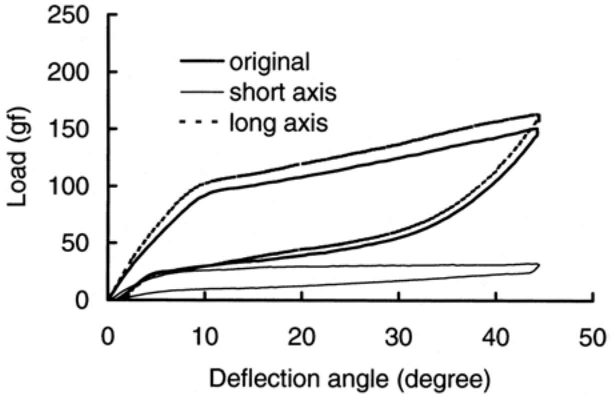

Figure 4 Typical load-deflection curves in the cantilever test of 71-59 wires.

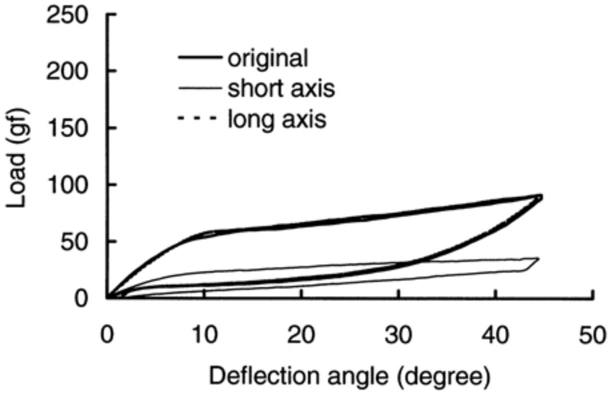

Figure 5 Typical load-deflection curves in the cantilever test of 61-49 wires.

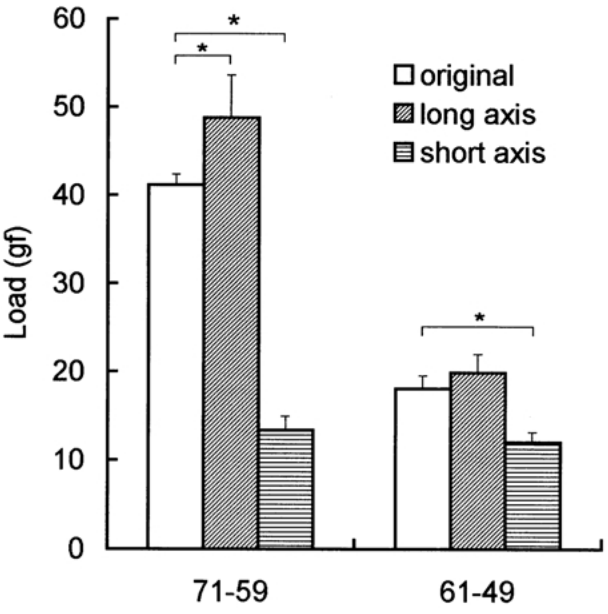

Figure 6 Change of SE-point load in the cantilever test. Error bars represent standard deviations. Asterisks indicate statistically significant differences ($p < 0.01$).

3.3. Three-point bending property

Figs 8 and 9 show typical load-deflection curves for each specimen in the three-point bending test. When the load was applied parallel to the long axis, increases in the load

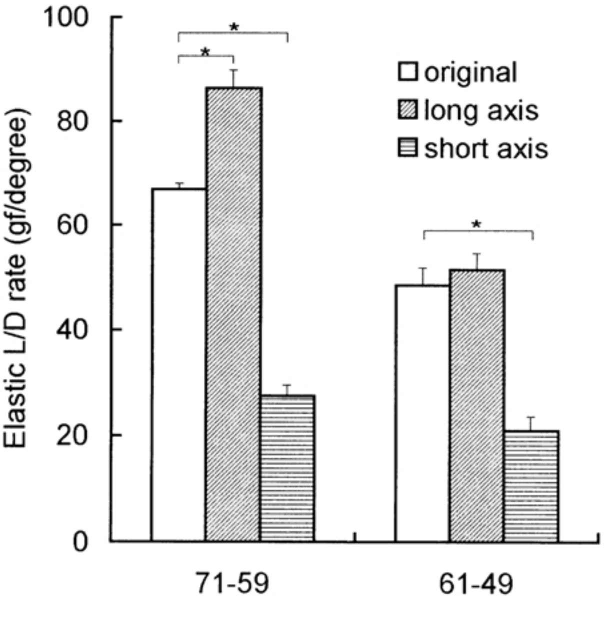

Figure 7 Change of elastic L/D rate in cantilever test. Error bars represent standard deviations. Asterisks indicate statistically significant differences ($p < 0.01$).

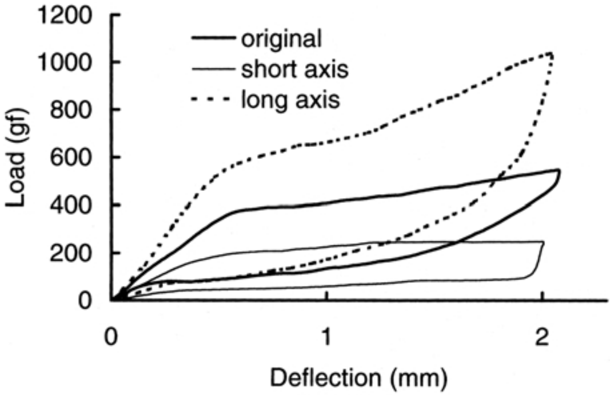

Figure 8 Typical load-deflection curves in three-point bending test of 71-59 wires.

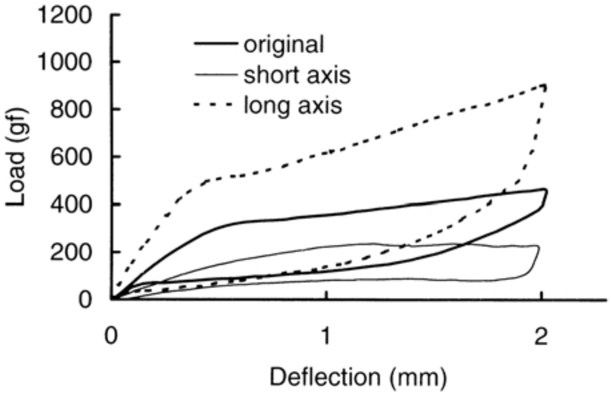

Figure 9 Typical load-deflection curves in three-point bending test of 61-49 wires.

level and in the inclination of elastic range were observed, while the load level and the inclination of the elastic range decreased in the short axis, compared with the original wire.

Fig. 10 shows the change of the SE-point load at the 1.0 mm deflection, and Fig. 11 shows the change of the elastic L/D rate. In 71-59, SE-point load changed from 135 gf (original wire) to 172 gf for the long axis, and to 59 gf for the short axis. In 61-49, SE-point load was less changeable, 78 gf for the short axis was larger than 71-59. In 71-59, elastic L/D rate changed from 706 gf/mm to 1106 gf/mm for the long axis, and to 468 gf/mm for the short axis. In 61-49, it changed from 674 gf/mm to 1025 gf/mm and 325 gf/mm, respectively. There were statistically significant differences from original wire in all conditions.

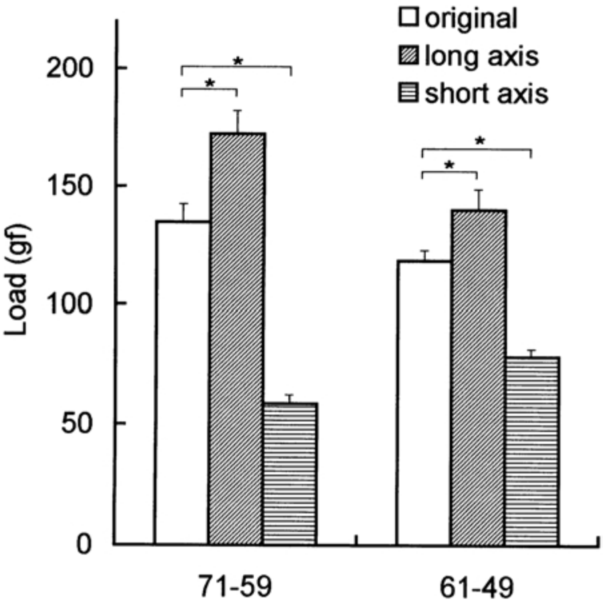

Figure 10 Change of SE-point load in three-point bending test wires. Error bars represent standard deviations. Asterisks indicate statistically significant differences ($p < 0.01$).

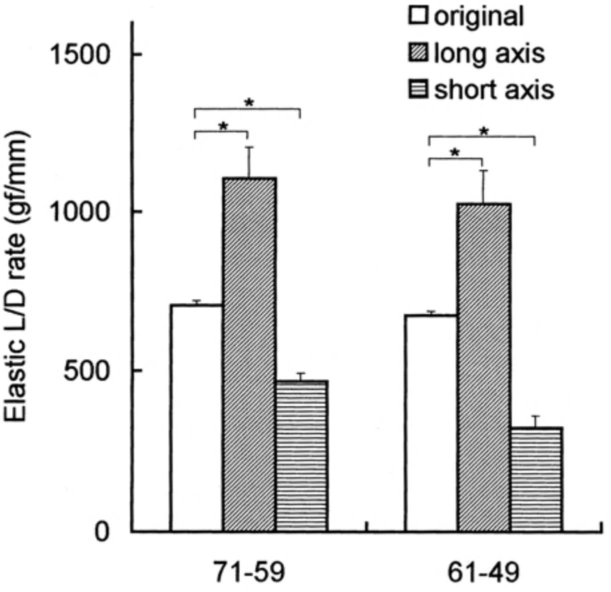

Figure 11 Change of elastic L/D rate in three-point bending test wires. Error bars represent standard deviations. Asterisks indicate statistically significant differences ($p < 0.01$).

4. Discussion

4.1. Method to transform the wire cross-section

The super-elastic Ti-Ni alloy wire can memorize a new shape if it is transformed while performing heat treatment at appropriate temperature [9, 10]. There are three types of shape-memory treatment for the super-elastic Ti-Ni alloy, which are medium-temperature treatment, low-temperature treatment, and aging treatment. The medium-temperature treatment is known to bring excellent mechanical properties, and has been widely used to perform shape-memory heat treatment of orthodontic super-elastic Ti-Ni alloy wire [3, 5, 11]. As a pilot trial, a transformation of the wire cross-section was carried out at room temperature, causing destruction in the margin of the transformed segment of the specimen. This was probably caused by work-hardening, resulting in deterioration of the mechanical properties. The temperature 300 °C, to which the pliers were heated in this study was selected by the practical reason for the transformation procedure. As shown in scanning electron microscope images of the transformed segment of the 61-49 (Fig. 12), destruction at the margin of the specimen and deterioration of its surface character were not observed.

From these results, it is possible to transform the wire cross-section directly by using heated pliers, suggesting the development of a simple transformation method for clinical orthodontic chair-side application.

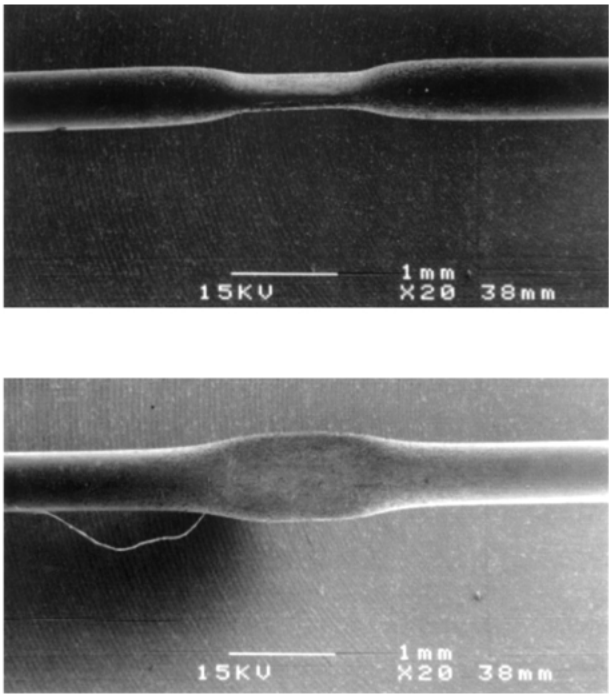

Figure 12 Scanning electron microscope images of the transformed 61-49 wires.

4.2. Anisotropic properties

Among the orthodontic super-elastic Ti-Ni alloy wires in the market, the SE-point load in the three-point bending test for round wires with diameter of 0.016 in (0.41 mm) was in the range of $20 \sim 90$ gf, while those for rectangular wires with diameter of 0.016 × 0.022 in (0.41 × 0.56 mm) was in the range of $60 \sim 180$ gf [12]. On the other hand, the hollow wires used in this research were of 0.71 or 0.61 mm diameter, larger in outer size than those mentioned. Despite their larger diameter, the SE-point load values of the two sizes of the hollow wires were in this range, 135 and 119 gf, as obtained in three-point bending test. By transforming the cross-sections of the two hollow wires, the long axis values increased to 172 gf and 140 gf, while the short axis values decreased to 59 and 78 gf, respectively. Therefore, it becomes possible to adjust the orthodontic force to a range suitable for an individual tooth movement by transforming the cross-section of the hollow wire.

From the results of the three-point bending test, anisotropic changes in the elastic L/D rate and the load level were observed. These parameters increased in the long axis direction and decreased in the short axis direction. On the other hand, in the cantilever test, the deflection seemed to be much transmitted to the part with the lower elastic L/D rate, resulting in a small change in the long axis direction.

Since the modulus of elasticity depends on the kind of materials, the bending property is fundamentally influenced by another factor, the moment of inertia, which differs according to the cross-sectional shape of the wires [8, 13]. The following formulae give the moments of inertia for a hollow circular wire (I), a hollow elliptical wire for the long axis (I'), and a hollow elliptical wire for the short axis (i') [14], the latter two cases being applicable to the transformed segment of the wire

$$I = \pi(D^4 - d^4)/64$$
$$I' = \pi(H^3 B - h^3 b)/64$$
$$i' = \pi(B^3 H - b^3 h)/64$$

where

D, outer diameter;
d, inner diameter;
H, outer diameter of long axis;
h, inner diameter of long axis;
B, outer diameter of short axis;
b, inner diameter of short axis.

The anisotropy following the transformation of wire cross-section depends on changes in this moment of inertia. The increase or decrease of the load in the load-deflection curve obtained from bending tests were recognized by this factor. Under the assumption that wall thickness of the hollow wire is not changed and the cross-section changes to a precise hollow ellipse by the transformation, the moment of inertia of 71-59, calculated from measurements of the transformed segment, is $10.2 \times 10^{-3}\,\mathrm{mm}^4$ in the long axis and $1.1 \times 10^{-3}\,\mathrm{mm}^4$ in the short axis. These values represent about 150% and 17%, respectively, compared with the value $6.5 \times 10^{-3}\,\mathrm{mm}^4$ for the original wire. Therefore, actual influence of the transformation of the wire cross-section on the bending property can be evaluated by the theoretical changes of the property relating to the moment of inertia.

If the assumed ideal transformation were applied to the whole specimen in the three-point bending test, the SE-point load should be 202 gf for the long axis and 23 gf for the short axis and the elastic L/D rate should be 1108 gf/mm and 119 gf/mm, respectively. While, the measured values for SE-point load were 172 gf and 59 gf/mm and those for the elastic L/D rate were 1106 gf/mm and 468 gf/mm, respectively. One of the main reasons for this difference should be that the transformation was applied only the restricted parts of the specimen. However, the degree of the difference from the calculated value was different for each parameter, the elastic L/D rate for the long axis was almost the same as calculated. This suggests that the influence of the transformation on the bending property appears to depend on the deformation mode in the deflecting process. Similar tendency was observed in the cantilever test, however, some parameters were less changeable, which is partly caused by less change in cross-sectional shape.

A practical and simple transformation method for the cross-section of hollow wire was developed for clinical orthodontics. By altering the cross-section of the hollow wire in accordance with the requirements of each case, it is possible to deliver suitable orthodontic force in different directions, for optimal movement of an individual tooth. Specifically, continuous, light, and appropriate orthodontic force is obtained toward the short axis by transforming the wire cross-section. Simultaneously, because a high elastic L/D rate is obtained in the long axis direction, the wire possibly deflects mainly along the short axis, making three-dimensional tooth movement achievable. When deployed as arch wires, customized to an individual case so as to provide optimal tooth movement according to individual parts of dental arch, this technique is believed to bring new method in orthodontic treatment.

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