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ORIGINAL ARTICLES

The super-elastic property of the Japanese NiTi alloy wire for use in orthodontics

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A new Japanese nickel-titanium (NiTi) alloy wire was developed by the Furukawa Electric Co., Ltd. of Japan. This wire was subjected to uniaxial tensile testing and a specially designed three-point bending test to determine the wire stiffness, and to evaluate springback, shape memory, and super-elasticity. The Japanese NiTi wire exhibited an unusual property termed "super-elasticity," which no other orthodontic wire has shown. This phenomenon was researched thoroughly. The wire delivered a constant force over an extended portion of the deactivation range. Among all the wires compared, Japanese NiTi alloy wire was the least likely to undergo permanent deformation during activation. The new alloy exhibited a specific stress–strain curve unlike those of the other tested materials. Stress remained nearly constant despite the strain change within a specific range. This unique feature is the manifestation of so-called super-elasticity. Heat treatment enabled the load magnitude at which super-elasticity is reflected to be influenced and controlled by both temperature and time. A unique and useful process was also developed so that an arch wire delivering various magnitudes of force for a given activation could be fabricated from the wire of the same diameter. The clinical application of wires of this new alloy should be more likely to generate a physiologic tooth movement because of the relatively constant force delivered for a long period of time during the deactivation of the wire. Japanese NiTi alloy should be considered an important material addition to clinical orthodontic metallurgy. (AM J ORTHOD DENTOFAC ORTHOP 90: 1-10, 1986.)

Key words: NiTi alloy, super-elasticity, shape memory, arch wires

Nickel titanium (NiTi) alloy was investigated and developed by the Naval Ordinance Laboratory in Silver Springs, Maryland, in the early 1960s. It has also been reported that this alloy has a unique property called shape memory.

Shape memory is a phenomenon occurring in the alloy that is soft and readily amenable to change in shape at a low temperature, but it can easily be reformed to its original configuration when it is heated to a suitable transition temperature.[1-3]

The shape-memory attributes of this alloy have attracted the attention and research endeavors of metallurgists in many countries. As a result it has been established that the NiTi alloy has excellent springback and super-elastic properties[4,5]; it has also been demonstrated that it has a high degree of resistance to corrosion.

The "super-elastic property" is a phenomenon that can be described briefly. The stress value remains fairly constant up to a certain point of wire deformation. At the same time, when the wire deformation rebounds, the stress value again remains fairly constant. Because

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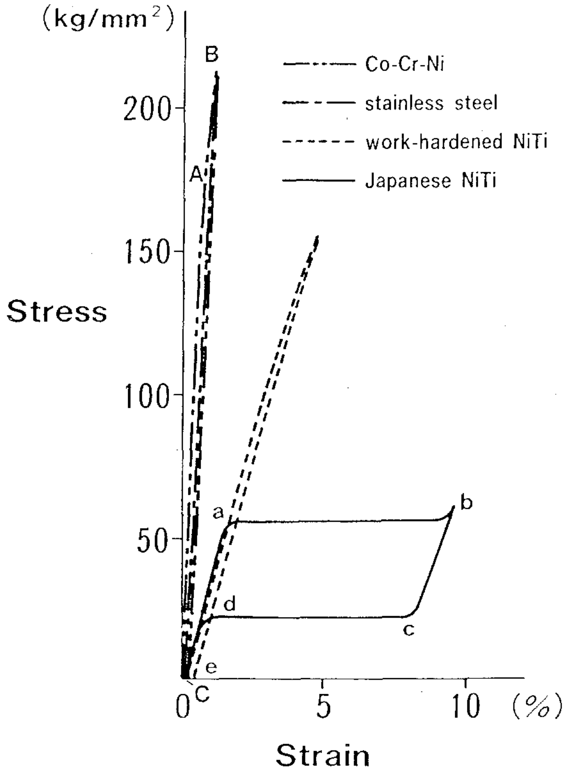

Fig. 1. Stress–strain curves for orthodontic wires of 0.016 inch in diameter at the moment of pulling and upon tensile release.

of such unique properties, NiTi alloy has been widely used in the industrial, medical, and other scientific fields.[2,6]

In clinical orthodontics, Andreasen and his associates were attracted by the unique properties inherent in NiTi alloy, such as the high elastic limit and the low elastic modulus. In 1971, they reported the results of their investigation for clinical use.[7] Subsequently, Unitek Corporation has produced this wire for the profession under the trade name of Nitinol. Nitinol has an excellent springback property,[8-11] but it does not possess shape memory or super-elasticity because it has been manufactured by a work-hardening process.[2]

In 1978, Furukawa Electric Co., Ltd. of Japan produced a new type of the Japanese NiTi alloy, possessing all three properties (excellent springback, shape memory, and super-elasticity).[12-15] The unique feature of the stress value remaining fairly constant during deformation and rebound is a very important concept of this entire investigation. Basic research was needed to study the Japanese NiTi alloy so that it might be used in clinical orthodontics to take advantage of the two unique properties of super-elasticity and shape memory.[12-17]

To thoroughly understand the super-elastic property of Japanese NiTi alloy wire, the major thrust of this report is focused on the following aspects.

1. Examination of the mechanical property of the wire
   a. Tensile tests
   b. Bending tests
2. Measurements of the influence of special heat treatment on the wire

METHOD AND FINDINGS

Examination of the mechanical property of the wire

Tensile tests. Uniaxial tensile testing was performed first because it is the most acceptable method to demonstrate clearly the comparative mechanical properties of wires.

The tensile strength was tested with the wire specimen attached to a steel plate with epoxy resin at 37° ± 1° C. Fig. 1 indicates the stress–strain curve. Comparison was made with other wire specimens such as stainless steel,* Co-Cr-Ni,† and Nitinol.‡ A specimen of the Chinese NiTi wire reported by Burstone was not available for inclusion in this test.[22] Four separate types of round wire 0.016 inch in diameter were selected. The elastic modulus was 17-20 × 10^3 kg/mm^2 for the stainless steel wire and 17-22 × 10^3 for Co-Cr-Ni. The elastic modulus of Nitinol wire was 5-6 × 10^3 kg/mm^2, showing the stress–strain curve to be almost straight. In contrast, a stress–strain curve of great significance was produced with the Japanese NiTi alloy wire, yielding a significantly higher value of elastic modulus than the Nitinol wire. When the stretch exceeded 2%, the stress value was not changed appreciably. When the strain was induced at 8%, it produced stresses of 55 to 58 kg/mm^2. When the wire specimen was then stretched 8% or more, the stress was increased further. This unusual property of the Japanese NiTi alloy wire as illustrated by the stress–strain curve is called "super-elastic property" (Fig. 1, a-b).

When strain was reduced, the stainless steel, Co-Cr-Ni, and Nitinol wires all exhibited almost straight stress–strain curves. In comparison, when strain was reduced, the Japanese NiTi alloy wire did not change proportionally to the stress decrease from 8% to 2%. There was no permanent set when the stress reached zero. This is also called "super-elastic property" (Fig. 1, c-d). The portion representing the super-elasticity was made much lower by decreasing the stress rather than by increasing it.

Bending tests. To determine the possible use of the super-elastic property in clinical orthodontics, a three-

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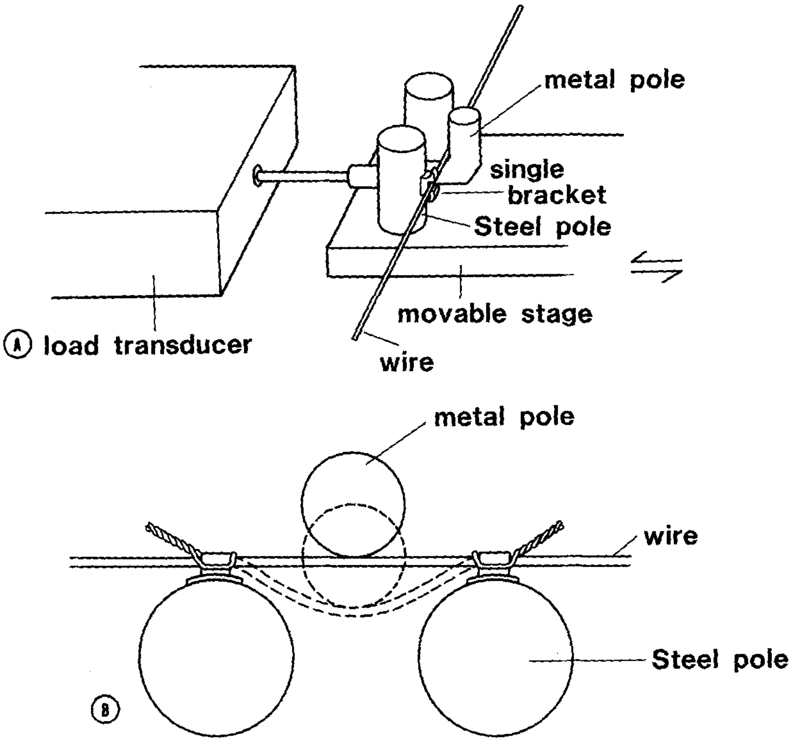

Fig. 2. Schematic drawing of instrumentation used in the three-point bending test. **A**, Side view. **B**, View from above.

point bending test was conducted in a specially designed situation similar to the conditions involved in moving teeth in the oral cavity.

The approved ADA standard method is a cantilever type of test. This method is an acceptable one to demonstrate the springback properties. Wires of good springback property increase the length and the angle of the specimen so that the super-elastic-like property appears even if the wires do not possess this feature.

As a result the ADA standard test method was not used in this investigation. Instead, a three-point bending test was designed because this would accurately differentiate the wires that do not possess super-elastic features. At the same time the three-point bending test actually simulates the application of wire pressure on the teeth in the oral cavity.

A three-point bending test was conducted by designing a bend test instrument as shown in Fig. 2. This was designed to clarify the relationship between the loading and deflection by determining the nature of the force being delivered during orthodontic treatment. A single bracket was attached on a steel pole, acting like a dental unit placed on a movable stage, so that the bracket span could be set at 14 mm. The test wire was held in place with a ligature wire in the slot with a known quantity of force. The midportion of the wire segment was then deflected 2 mm at the speed of 0.1 mm/min under the pressure from a metal pole 5 mm in diameter.

Fig. 3 shows the results of the bending test with several different types of 0.016 inch wires. The load deflection curves represented by both stainless steel and Co-Cr-Ni wires showed a linear relationship up to 0.7 mm. When it exceeded 0.7 mm, its increasing ratio was gradually reduced. When the amount of deflection was 2.0 mm, the load was 1320 to 1370 g, and on reducing the deflection to 1.8 mm, the load decreased rapidly. The subsequent decreasing ratio was proportional and the permanent deformation was 0.65 mm. The dotted line in Fig. 3 represents Nitinol, which indicates the applied load moment for the corresponding deflection of up to 2 mm. The load deflection curve represented by Nitinol was almost linear along with the additional loading. When the deflection distance of 2.0 mm was reached, the load was 790 g. As the deflection was removed, the load was decreased in a similar manner as indicated by the stainless steel and Co-Cr-Ni wires. Fig. 3 shows the load deflection curve of the Japanese NiTi alloy wire to be almost linear up to 0.7 mm. The load-increasing ratio was decreased, and the load was 650 g when the deflection was 2.0 mm. During the decrease of the deflection, the load decreased rap-

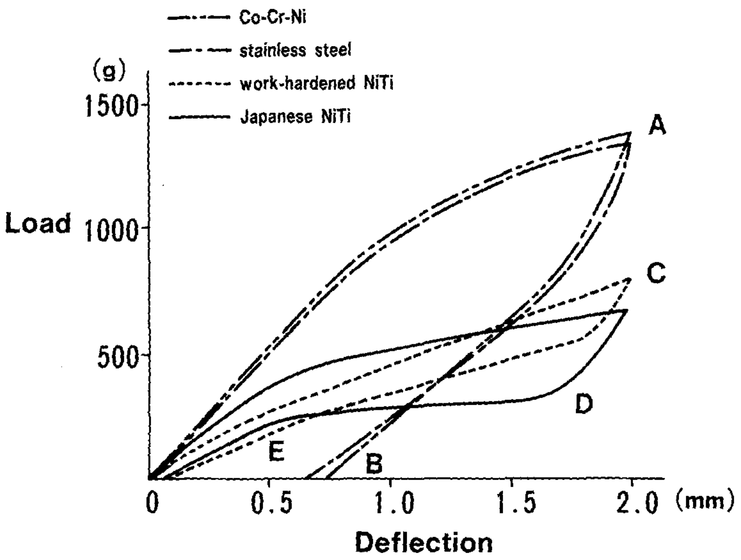

Fig. 3. Load deflection curves produced by the three-point bending test.

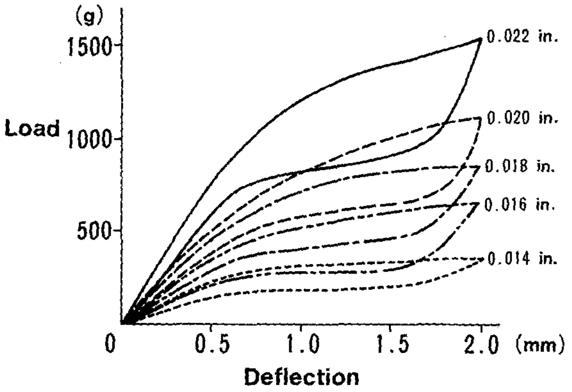

Fig. 4. Load deflection curves on five different diameters of the Japanese NiTi alloy wires.

idly in the range of the deflection curve between 2.0 mm and 1.6 mm. When the deflection was decreased 1 mm from 1.6 mm to 0.6 mm, the load was decreased only a small amount within the range of 250 to 350 g. When the deflection was less than 0.6 mm, the load was decreased within a given proportion and the permanent set was only 0.01 mm. By evaluating the test results, both the bending test and the tensile test demonstrated that Japanese NiTi alloy wire possesses super-elastic property.

Fig. 4 shows the result of the bending test of five different diameters—0.014, 0.016, 0.018, 0.020, and 0.022 inch—of the Japanese NiTi alloy wires using the same testing instrument. The diagram illustrates the load needed (vertical component) to produce the deflections of up to 2 mm for the selected gauges.

Measurement of the influence of special heat treatment on the wire

Heat treatment of NiTi alloy does make a dramatic change in its mechanical property.[23] To attain optimal use of the super-elastic property in clinical orthodontics, the influence of a varied series of heat treatments was studied. A comparative analysis was conducted for this property before and after being subjected to heat using a 0.016 inch Japanese NiTi alloy wire. Heat treatment was produced by immersion of the wire in a nitrate salt bath. The temperature levels applied to the wire were 200° C, 300° C, 400° C, 500° C, and 600° C, respectively. The heat exposure periods were 5, 10, 60, and 120 minutes. A total of 20 different variations of heat treatment were used. After the heat exposure, the wire was quenched in water. The mechanical properties of the wire were then determined by conducting a series of bending tests on the bend test instrument (Fig. 2). The test was conducted at a temperature of 37° ± 1° C.

No significant change of mechanical property of wire was noted at 200° C or 300° C. Figs. 5 through 7 show the results of the bending test at temperatures of 400° C, 500° C, and 600° C, respectively. Fig. 5 shows the results of the heat application at 400° C. The portion indicating the linear relationship between the load and the deflection showed that only a small amount of heat treatment effect was noted. In the portion showing super-elasticity, the load value was reduced along with the lapse of time.

In Fig. 6, at 500° C temperature, the load portion

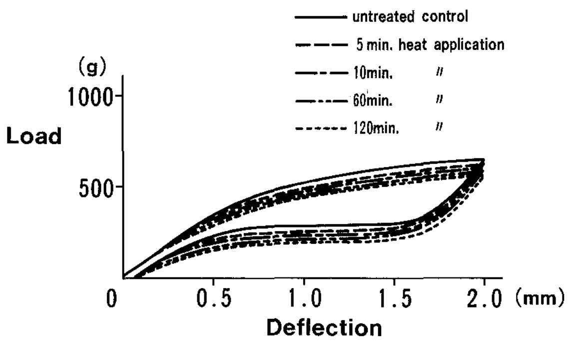

Fig. 5. Results of the heat application on 0.016 inch Japanese NiTi alloy wire at 400° C.

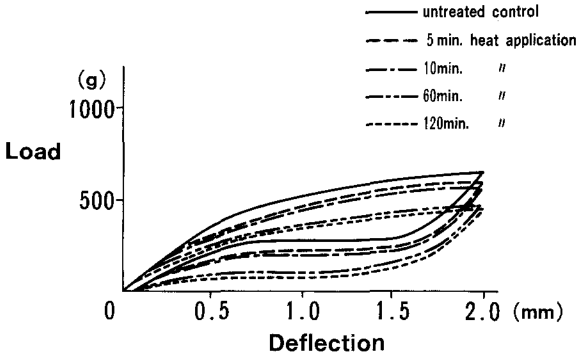

Fig. 6. Results of the heat application on 0.016 inch Japanese NiTi alloy wire at 500° C.

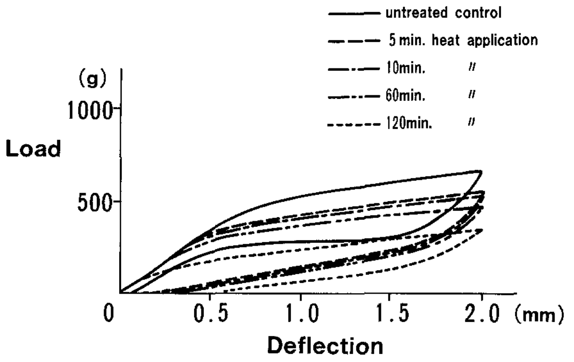

Fig. 7. Results of the heat application on 0.016 inch Japanese NiTi alloy wire at 600° C.

showing super-elasticity was definitely decreased. The decrease of the load was greater than at 400° C (Fig. 5). The wire, treated at 500° C for 120 minutes, had a super-elastic portion of approximately 50 g load along with the gradual removal of load. The super-elastic load portion decreased considerably in comparison to the load of 300 g in the untreated control wire (Figs. 3 and 4).

Fig. 7 indicates the results after heat application at 600° C. Super-elasticity and the good springback property of the wire were almost completely lost even when the heat exposure was for only 5 minutes.

DISCUSSION

Evaluation of findings

Tensile tests. This basic test was conducted to analyze the mechanical properties of the wire. As seen in Fig. 1, the stress–strain curves of stainless steel and Co-Cr-Ni alloys, indicated as 0-A, demonstrated elastic deformation. This revealed that the relationship between stress and strain was proportional. When the stress was increased, as indicated by A-B, permanent deformation was produced. In other words, the stress increase was disproportional to the strain increase. Subsequently, when the stress was removed, the relationship between the stress and the strain was almost proportional and permanent deformation remained as indicated by C-0.

Nitinol, the work-hardened NiTi alloy wire, possessed a much lower elastic modulus and could be deformed almost five times greater, but the pattern of stress–strain curve was quite similar to that of the stainless steel and Co-Cr-Ni wires.

The Japanese NiTi alloy wire produced a completely different curve pattern as shown in Fig. 1. When the wire was stretched up to 2%, as indicated by 0-a, the stress and strain were almost proportional. As indicated by a-b, the stress was not subsequently changed in spite of the strain increase. This appeared to be similar to the curve shown by the plastic deformation, but when the stress was removed, the phenomenon indicated by c-d was similar to a-b. This phenomenon is the super-elastic property of this alloy, which shows a completely different property compared with the other wire samples.

The physical behavior of the NiTi alloy wire can be interpreted and explained from a metallurgic analysis. It is a generally accepted fact that NiTi alloy is a nearly equi-atomic intermetallic compound that incorporates a variety of properties that can be controlled by the manufacturing method. A given zone lies between high and low temperature ranges. At the high temperature range, the crystal structure of NiTi alloy is in an austenite phase, which is a body-centered cubic lattice (CsCl type B2 structure). The martensitic phase, which is a close-packed hexagonal lattice, is at a low temperature range. By controlling the low and high temperature ranges, a change in crystal structure called martensitic transformation can be produced. This phe-

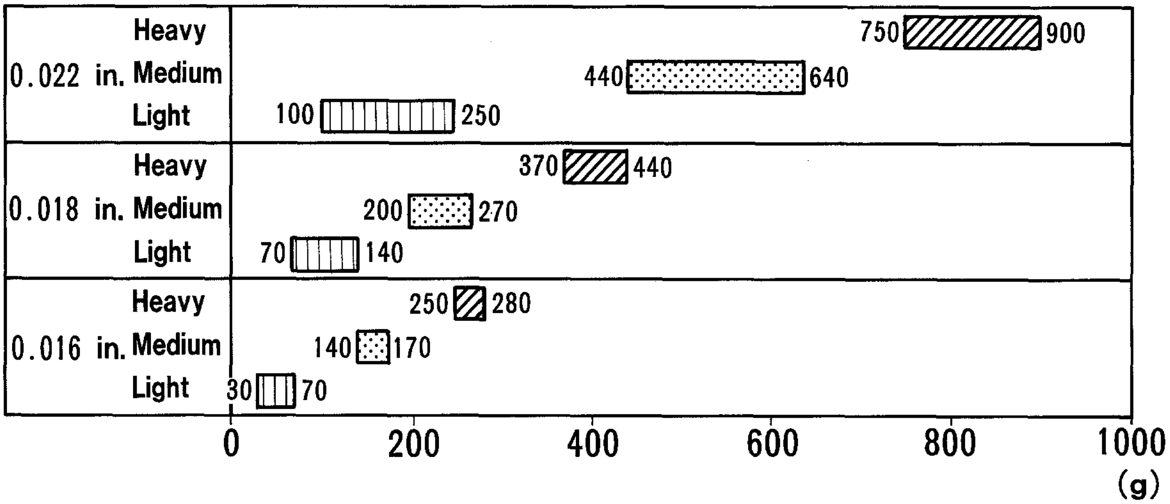

Fig. 8. Force ranges for light, medium, and heavy Japanese NiTi alloy wires in 0.016, 0.018, and 0.022 inch diameter wires. Range of super-elasticity is indicated on the graph.

nomenon is said to cause a change in its physical property.[1,3,18] In the martensitic phase, which has a low temperature range, this metal is ductile and acts like a safety fuse to readily induce a change of shape. In the austenite phase in the high temperature range, it is more difficult to induce deformation.

When an external force is applied, the deformation of most metals is induced with a slip of lattice; the deformation of NiTi alloy is induced with martensitic transformation. The martensitic transformation can be reversed by heating the alloy to return to the austenite phase and it is gradually transformed by reversing back into the energy stable condition.[1,3,18-20] This means that the alloy can return to the previous shape. This phenomenon is called shape memory. A metal with this kind of phenomenon could demonstrate other properties. One of the most remarkable properties is super-elasticity. This can be produced by stress, not by temperature difference, and is called stress-induced martensitic transformation.[4,21] Martensitic transformation begins when an external force is applied in such a manner that the stress exceeds a given amount. Even when strain is added, the rate of stress-increase levels off due to the progressive deformation produced by the stress-induced martensitic transformation, indicating a movement similar to the slip deformation. Again, this phenomenon is the so-called super-elasticity. On the other hand, if the stress is diminished, the NiTi alloy returns to the previous shape without retaining the permanent deformation because of the characteristics of returning to the austenite phase within a given temperature range.

As already described, Nitinol, the commercial NiTi alloy wire used in the comparative experiment, does not possess super-elasticity, even though it belongs to the same category as NiTi alloy wire. In Nitinol the stress was increased in proportion to the strain increase, which is similar in pattern to the stainless steel and Co-Cr-Ni wires.[12-15] As shown in Fig. 1, in which the modulus and limits of elasticity are low in the martensitic phase of NiTi alloy wire, both of these properties are improved greatly by the work-hardening process. This wire primarily follows the martensitic phase, which does not exhibit super-elasticity because its shape memory has been diminished by work-hardening during the manufacturing process.

On the other hand, the Japanese NiTi alloy wire used in this investigation was manufactured by a different process than Nitinol, and demonstrated the super-elastic property. This finding can be expanded with the following explanation. In the evaluation of findings for the metallurgic approach, as indicated by the tensile test diagram, the portion 0 to a in Fig. 1 illustrates an elastic deformation that occurs with the strain range of 0% to 2% in the austenite phase. The martensitic transformation begins at the 2% strain level and the transformation continues up to the 8% to 10% strain level. When the martensitic transformation is completed, the whole specimen is transformed into the martensitic phase; when this occurs, the stress increases because of the elastic deformation. When the strain is removed, as indicated by b-c in Fig. 1, the stress decrease is linear because the elastic deformation occurs in the cross-packed hexagonal lattice. Later, as indicated by c-d, the martensitic transformation occurs again in the direction of the austenite phase. When the transfor-

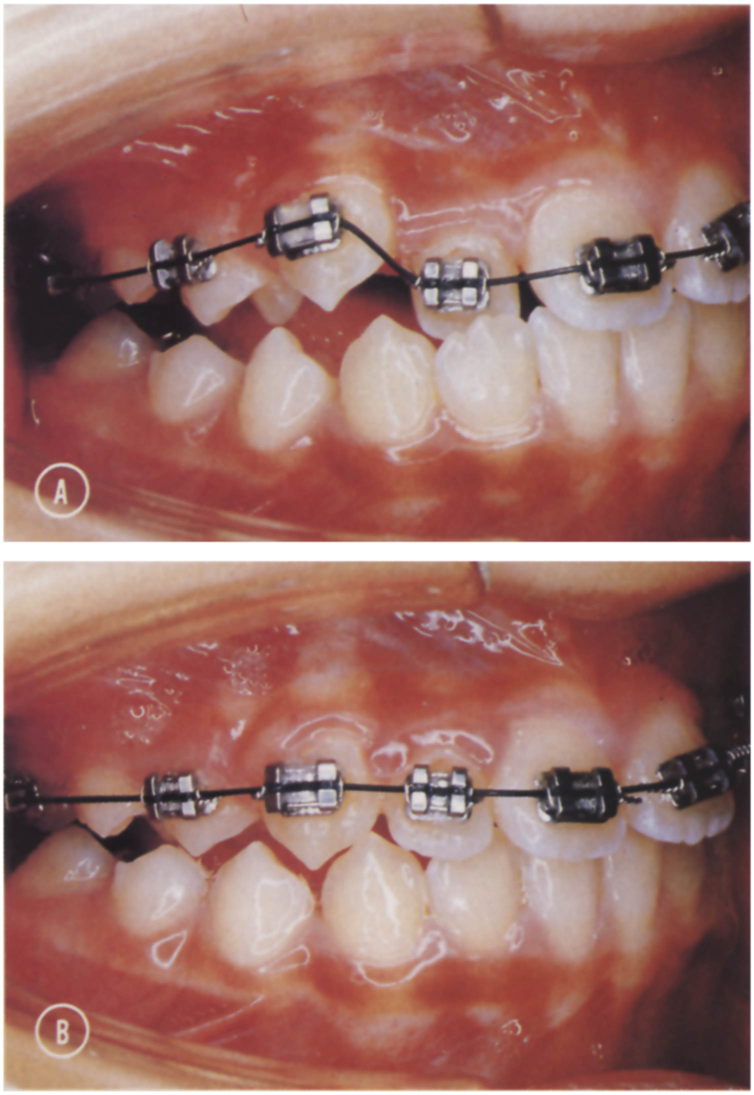

Fig. 9. A, Medium preformed Japanese NiTi alloy wire, 0.016 inch in diameter, tied into a lingually locked lateral incisor. **B,** Two months later. There was no permanent deformation of the wire in spite of the very sharp bends.

mation is completed, as indicated by d-e, the elastic deformation occurs in the austenite phase and the stress can be considered to decrease linearly.

As indicated in the metallurgic analysis, the Japanese NiTi alloy wire possesses so-called super-elastic properties as illustrated in the ranges from a to b and c to d.

Bending tests. To properly evaluate the wire for clinical application, the tensile tests, which demonstrate the super-elastic property alone, were not enough. A separate bending test was also necessary to properly determine the practical value of this wire.

The ADA has developed a standardized test method that requires a cantilever type of deformation. Using this test method on selected wires, the results were reported at the annual meeting of the Japanese Dental Material Association at Kyoto in 1982.[15] By means of the same test method, Burstone has recently reported similar data on the Chinese NiTi wire.[22]

The results of Watanabe's study did not reveal much difference between the work-hardened NiTi alloy wire and the Japanese NiTi alloy wire. When a cantilever type was used to test the bend, a curve was formed because of the distance between the fixed portion and the point where pressure was applied. There were two important factors involved in the cantilever test method. First, the length of the wire increased. As a result the load weakened. Second, the angle of the wire closest

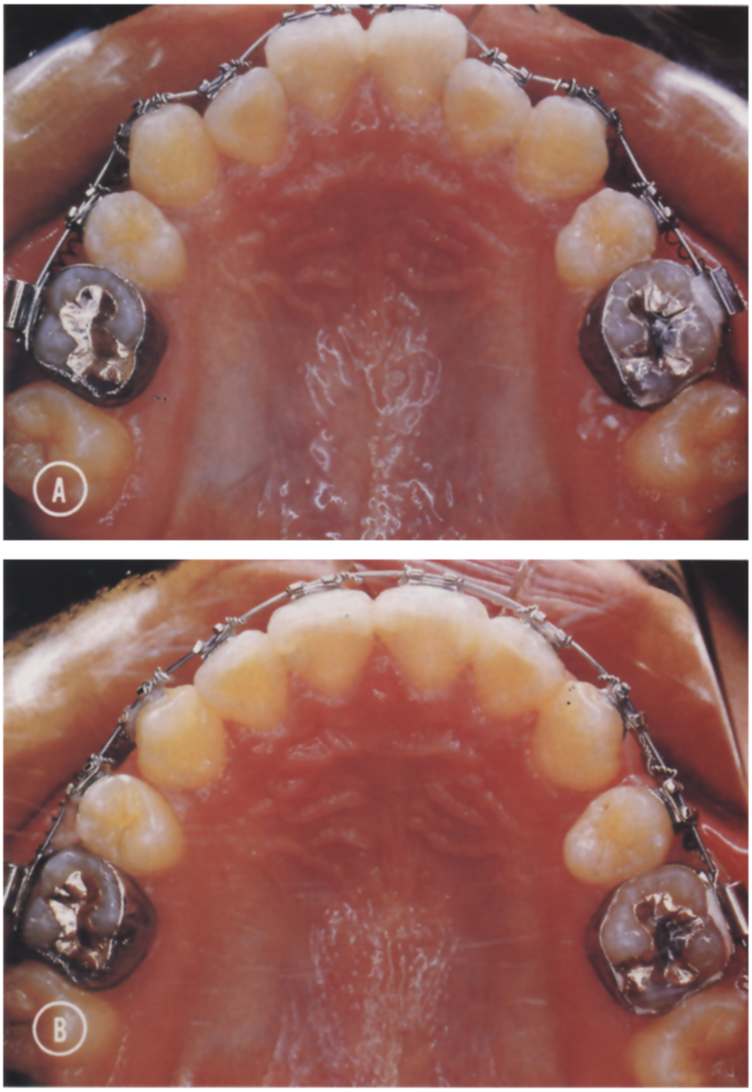

Fig. 10. A, Occlusal view of light wire 0.018 inch in diameter. **B,** One month later. No wire adjustment was made during the entire period.

to the attached portion became smaller. As a result even wires with no super-elastic properties would respond in a graph resembling the presence of super-elasticity. For these reasons the cantilever instrument was not considered a reliable method to test for super-elastic property of wires. By checking the data, the work-hardened Nitinol had an excellent springback property, but did not have the essential super-elastic property. However, when it was subjected to the cantilever test, it formed a curve similar to the material with super-elastic property because the load was gradually reduced even though the deformation was increased. This created a possibility of a source of error by misinterpreting the result. For this reason the three-point bending test was devised to accurately differentiate the presence of super-elastic properties of wires (Fig. 2).

According to test results, both stainless steel and Co-Cr-Ni wires produced heavy loads with small amounts of deflection as indicated by the component 0-A in Fig. 3. Also, as indicated by 0-B, these materials tended to produce permanent deformation making a smaller range of action. Recent histologic studies on tooth movement have indicated that light continuous force is more effective than heavy intermittent force. Consequently, orthodontic wires of excellent spring back property and low stiffness—in other words, wires with great elastic limit and low elastic modulus—should be adopted for clinical application. In consid ering these factors, stainless steel and Co-Cr-Ni wires did not meet these requirements because in clinical application the orthodontic force was rapidly diminished when the tooth moved. In comparison, the work-hardened NiTi alloy wire produced light forces and the least amount of deformation. As indicated by the O-C component of Fig. 3, load and deflection were almost proportional, reducing the force accordingly when the tooth moved.

In contrast, the Japanese NiTi alloy wire possessed the property in which the load became almost even as indicated by D-E, even when the deflection was decreased. Again, this is termed ''super-elastic property'' and is physiologically compatible to the tooth movement because this new type of arch wire can provide continuous force for a long period during the deactivation of the wire.

Heat treatment of the wire. At the present state of the metallurgical art, it was difficult but possible to accurately control the martensitic temperature, which revealed the level of activity of super-elastic property of the wires. This can be described as the critical point at which the characteristics of super-elastic property were displayed when the stress was applied and when the stress was relieved. Since an ideal optimum force is essential for effective tooth movement, use of the super-elastic properties of the wires would seem highly desirable.

Honma and Takei[23] have reported on the martensitic temperature range changes in relation to the electrical resistance present in the NiTi alloy. Therefore, heat treatment was made to study the effect of temperature and time on the super-elasticity of the Japanese NiTi alloy wire.

The results were as follows. The effects of temperature were negligible up to 500° C in the linear portion where the elastic deformation was indicated and the super-elasticity level was lowered as illustrated in Figs. 5 and 6. For this reason, the martensitic temperature was changed without affecting the integrity of the wire. The amount of force indicating super-elasticity was lowered also in relation to the duration of the heat treatment.

By using this knowledge of the behavior of super-elasticity, which can be influenced by temperature and time, it is possible to produce an individualized force in a preformed arch wire of the same diameter without fabrication of any loops. It is also possible to modify the amount of orthodontic force in an individualized segment of the arch wire. For example, by applying controlled heat with adequate temperature and time on the anterior segment of the arch wire, the amount of force within the anterior segment can be decreased only if the posterior segment arch wires are not disturbed.

Clinical application

Since the metallurgical tests have determined that Japanese NiTi alloy wire is potentially useful and effective in the clinical orthodontic setting, arch wires have been fabricated to enhance the efficiency of the multibracketed technique.

For this study three sizes of Japanese NiTi alloy wires—0.016 inch (0.41 mm), 0.018 inch (0.45 mm), and 0.022 inch (0.56 mm)—were individualized to an ideal arch form of typical average Japanese maxillary and mandibular arches. Each size of arch wire was fabricated to three force types: light, medium, and heavy. There were 18 specimens* (Fig. 8).

Two cases are shown to depict rapidity of movement and lack of permanent wire deformation. Fig. 9, *a* depicts a lingually locked lateral incisor. A 0.016 inch medium preformed arch wire was tied in. This is a sharp bend distal to the lateral incisor bracket and mesial to the canine bracket. Because of the super-elasticity, the wire was easily tied in and did not cause a great deal of discomfort to the patient. Fig. 9, *b* shows the condition without any adjustment of the arch wire 2 months later when the alignment was completed. Because of the constant light continuous force, the lingually locked lateral incisor and the canine were effectively aligned. It should be noted that the sharp bend at the lateral and canine areas in the arch wire did not create a permanent deformation to the arch wire.

Fig. 10, *a* illustrates an extraction case with both lateral incisors approximately 2 mm in linguoversion. A 0.018 inch light preformed arch wire was tied in. As a result the wire displayed a great degree of deformation. Fig. 10, *b* shows the condition 1 month later. No wire adjustments were made in either case during the entire period. Due to the super-elasticity of the arch wire, tooth movement occurred effectively and the patient did not experience discomfort. The teeth moved physiologically because the wire delivered a relatively constant force for a long period during the deactivation of the wire.

CONCLUSION

NiTi alloy wire already used in clinical orthodontics is the work-hardened type wire called Nitinol. The Japanese NiTi alloy wire developed by Furukawa Electric Co., Ltd. possesses excellent springback property, shape memory, and super-elasticity. In the hope that

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*Sentalloy, Tomy Inc., Tokyo, Japan; Sentinol, GAC International, Inc., Commack, N.Y.

this new type of wire might be used effectively in orthodontics, the tensile test, the three-point bending test, and the evaluation of the influence of heat treatment were conducted to test for super-elasticity.

1. As shown in the tensile test, the newly developed Japanese NiTi alloy wire does exhibit super-elastic properties indicating an area of definite amount of stress in spite of the changes in the strain rate. By contrast, the stainless steel, Co-Cr-Ni, and Nitinol wires showed that the relationship between the stress and strain is proportional.
2. Three-point bending test results indicated that Nitinol wire provides a light force and a lesser amount of permanent deformation in comparison with stainless steel and Co-Cr-Ni wires. The load and the deflection are almost proportional because of the lack of super-elastic property. The Japanese NiTi alloy wire possessed super-elastic properties whereby the load became almost even when the deflection was decreased in the bending test. This feature provides a light continuous force so that an effective physiologic tooth movement can be delivered.
3. At the time of this research, the Chinese NiTi wire that Burstone reported was not available for a comparative test.[22] Further research will be focused on a comparison of the Chinese NiTi wire with the Japanese NiTi alloy wire.
4. The relationship between the temperature and time of the heat treatment of the Japanese NiTi alloy wire was studied to optimize the super-elastic properties of the alloy. When the heat application was raised to 500° C, the force level indicating the super-elastic property could be reduced. Thus, arch wires providing a different magnitude of force can be fabricated from the wires of the same diameter. In addition, in the preformed arch wire, different magnitudes of force can be produced by controlling the temperature and time in the desired section of the arch wire.
5. Super-elasticity is especially desirable because it delivers a relatively constant force for a long period ot time, which is considered a physiologically desirable force for tooth movement.
6. By evaluating clinical experience with the Japanese NiTi alloy wire, many possibilities exist with the use of its super-elastic property.

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