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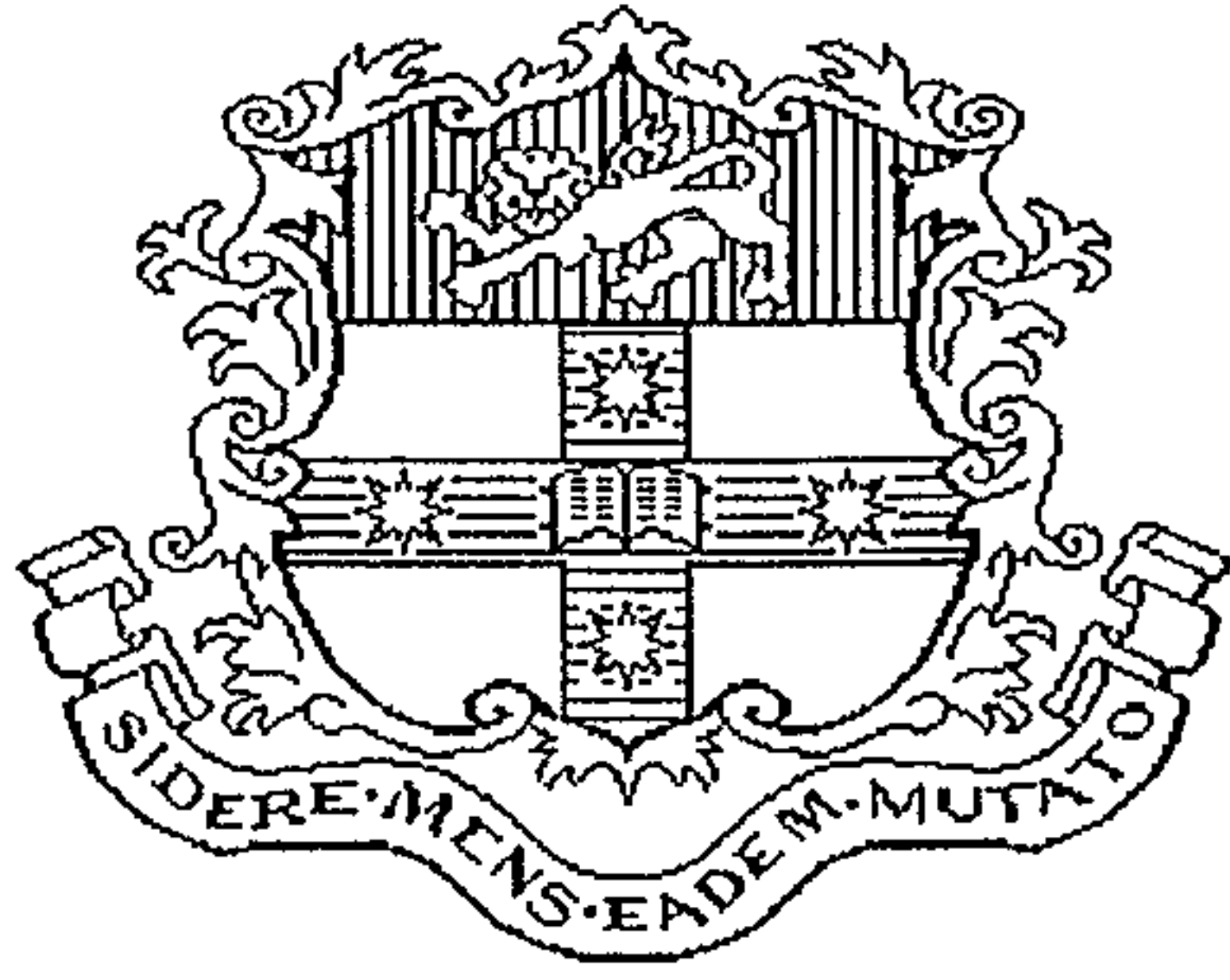
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A Comparison of the Tensile Properties of Nickel Titanium Orthodontic Wires

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A thesis submitted in partial requirement
for the degree of

Master of Dental Science

Discipline of Orthodontics
Faculty of Dentistry
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August 1995

Dedication

To my wife Margot, who I love and admire. She supported and encouraged me untiringly during the preparation of my thesis and the completion of the MSc program.

Table of Contents

<i>Dedication</i>	<i>ii</i>
<i>Table of Contents</i>	<i>iii</i>
<i>List of Illustrations</i>	<i>v</i>
<i>List of Tables</i>	<i>vi</i>
<i>Acknowledgments</i>	<i>vii</i>
<i>Declaration</i>	<i>viii</i>
<i>Abstract</i>	<i>ix</i>
1. Introduction	1
2. Aims and Objectives	2
3. Review of the Literature	3
3.1 Tensile test of orthodontic wires	3
3.2 Nickel titanium orthodontic wires and superelasticity	4
3.2.1 Superelasticity and shape memory	6
3.2.2 Thermally induced martensite and shape memory	7
3.2.2.1 One-way shape memory.	8
3.2.2.2 Two-way shape memory	8
3.2.3 Stress induced martensite and pseudoplasticity	9
3.3 Other testing methods for orthodontic wires	10
3.3.1 Bending tests	10
3.3.2 Torsional tests	11
3.3.3 Differential thermal analysis	11
3.3.4 Dynamic mechanical analysis	12
3.3.5 X-ray diffractometry	12
4. Materials and Methods	13
4.1 Materials	13
4.2 The tensile test	14
4.3 Statistics	17
5. Results	18
5.1 Tensile properties at ambient temperature.	18
5.2 Elastic modulus.	22
5.3 Temperature effect on transformation stress (σ_{Ms})	25
5.4 Elongational properties of the superelastic wires	25
5.5 Diameter of wires	27
5.6 Statistics	27

6.	Discussion	28
6.1	Stainless steel	28
6.2	Nitinol wire	30
6.3	Superelastic nickel titanium orthodontic wires	32
6.3.1	Before the stress induced phase change	32
6.3.2	The phase change	33
6.3.3	After the phase change	33
6.4	Load magnitude and tooth movement	34
6.4.1	Other evidence for light loads being optimal	35
6.5	Clinical selection of wires	36
7.	Conclusions	40
8.	Future Research	42
Appendix 1.	Tensile Test Data at Ambient Temperature	43
Appendix 2.	Tensile Test Data at Mouth Temperature	52
Appendix 3	Statistical Analyses	60
Appendix 4	1994 IADR Meeting, Australia and New Zealand Division: Abstract No. 81.	67
	Bibliography	68

List of Illustrations

- Figure 3.1 Thermally induced martensitic transformation of a superelastic Ni-Ti wire showing the martensitic transformation on cooling from M_S to M_f and reverse transformation back to the austenitic phase on heating from A_S to A_f (Duerig and Pelton 1994). 6
- Figure 3.2 Stress induced martensitic transformation of a superelastic Ni-Ti wire indicated by the loading pseudoplastic plateau from M_S to M_f and reverse transformation back to the austenitic phase indicated by the unloading pseudoplastic plateau from A_S to A_f (Kousbroek 1984). 9
- Figure 4.1 Ni-Ti wires used in this study. 14
- Figure 4.2 The universal testing machine (Shimadzu, Autograph AG-50NE). 15
- Figure 4.3 Steel grips for holding the test wires. 16
- Figure 4.4 Temperature control arrangement within the water bath, showing the copper coil through which water flowed at a thermostatically controlled temperature. 17
- Figure 5.1 Representative stress/strain curves of four wires at ambient temperature showing a stainless steel wire (SS), a non-superelastic wire (NT) and two superelastic Ni-Ti wires (SE & TP). 18
- Figure 5.2 Classical linear stress/strain curve illustrating 0.1% YS corresponding to 0.1% permanent yielding, shown by the dotted line parallel to the linear slope projected back to the x-axis. 19
- Figure 5.3 Superelastic Ni-Ti wires tensile tested at ambient temperature. 21
- Figure 5.4 Superelastic Ni-Ti wires tensile tested at mouth temperature. 21
- Figure 5.5 Stress/strain curve of a typical superelastic Ni-Ti wire showing σ_{M_S} , PPR and MEE. 24
- Figure 6.1 Different samples of Nitinol a, b and c elongated to 4%, 5% and 6% during cyclic tensile testing at mouth temperature, showing approximately 0.3%, 0.5% and 0.8% permanent yielding, respectively. 31
- Figure 6.2 NT elongated to 4% and CX to 7% during cyclic tensile testing at mouth temperature, showing approximately 0.3% and 0.1% permanent yielding; respectively. 34

List of Tables

Table 3.1	Tensile properties from a study by Watanabe (1982).	4
Table 4.1	Wires tensile tested in the present study.	13
Table 5.1	Tensile properties at ambient and mouth temperatures.	22
Table 5.2	Elastic moduli of first and second slopes at ambient and mouth temperatures.	23
Table 5.3	New tensile parameters for Ni-Ti orthodontic wires used in the present study.	24
Table 5.4	Comparison of transformation stress (σ_{Ms}) or pseudo-0.1% YS at 23°C and 37°C.	25
Table 5.5	Elongational properties of superelastic Ni-Ti wires tested at ambient and mouth temperatures.	27
Table 6.1	Comparison of tensile properties of stainless steel wires including those obtained in the present study.	28
Table 6.2	Comparison of Standards Association of Australian typings of stainless steel wires, A.J.Wilcock gradings and UTS results from the present and other studies of Wilcock wires.	29
Table 6.3	Reported tensile properties for 0.4 mm diameter Nitinol wires.	31
Table 6.4	Comparison of different wire types (Kapila and Sachdeva 1989), with updates.	39

Acknowledgments

Deep gratitude is expressed to the following people:

Dr. Toshiko Mori, Biomaterials Department, Faculty of Dentistry, University of Sydney, for her supervision, expertise and guidance throughout this study.

Professor Milton R. Sims, Head - Discipline of Orthodontics, Faculty of Dentistry, University of Sydney, who supervised and advised during the preparation of this thesis.

Dr. Kath Arneman, Faculty of Dentistry, University of Sydney, who advised in the presentation of this thesis.

Adrienne Kirby, Biometry Department, University of Sydney, who statistically analysed and interpreted the data for this thesis.

Ken Tyler, Biomaterials Department, Faculty of Dentistry, University of Sydney, who assisted and advised on equipment for this study.

Dr Sushit Poolthong and Dr Peter Chung, Biomaterials department, Faculty of Dentistry, University of Sydney, for advice and assistance.

This study was supported by an Australian Society of Orthodontists grant.

Declaration

CANDIDATE'S CERTIFICATE

This is to certify that the work in this thesis was carried out by the candidate in the Orthodontic Unit, University of Sydney, and has not been submitted to any other university or institution for a higher degree.

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Abstract

Tensile test data are predominantly available for stainless steel wires, but not for nickel titanium (Ni-Ti) wires for which bending test data are mainly available. The tensile test is more appropriate than the bending test for determining many properties of a wire, as it introduces fewer variables.

The aim of this study was to gain tensile data and assess appropriate tensile parameters to enable comparisons of nickel titanium (Ni-Ti) wires, which would aid in the clinical selection of these wires.

Eight commercial 0.4 mm diameter Ni-Ti wires were tested at a cross-head speed of 1 mm/min at ambient and mouth temperatures. At least five specimens were tested for each wire. A stainless steel wire was tested for comparative purposes. A preliminary unloading study at mouth temperature was also undertaken.

All Ni-Ti wires tested, except Nitinol, showed distinct pseudoplastic behaviour at ambient and mouth temperatures. This finding indicated that the superelastic Ni-Ti wires had undergone stress induced phase transformation. However, Nitinol did show some pseudoplasticity, as it showed non-linear elasticity on its unloading curve. All Ni-Ti wires showed an initial linear stress/strain relationship, and all including Nitinol showed a non-linear elastic stress/strain relationship, that is, they showed evidence of some pseudoplastic behaviour. New parameters such as the transformation stress (σ_{Ms}) recorded at the 'pseudo'-0.1% yield strength (YS), the pseudoplastic range (PPR) and the maximum elastic elongation (MEE) recorded at 0.1% YS were introduced.

The elastic moduli were 27-42 GPa for the first slopes. The t-test showed that the values were significantly ($P < 0.05$) reduced in the second slopes for most superelastic wires. Using Tukey's honestly significant difference (HSD) test at the critical value of $P < 0.05$, the wires were ranked for the different parameters. For superelastic wires, the PPR was 2-6%, the σ_{Ms} was 300-490 MPa, the MEE was 8-10%, and ultimate tensile strength (UTS) was 1250-1500 MPa. These new parameters were considered to be important tensile clinical parameters for the superelastic Ni-Ti wires.

All Ni-Ti wires tested showed non-linear stress-strain relationships, and all except Nitinol showed 'superelasticity'. Superelasticity refers to high elastic elongation. The presence of the second slope for the superelastic Ni-Ti wires indicated the occurrence of the austenitic to martensitic stress-induced phase change.

The unloading curve of the CX Enterprise Chinese Ni-Ti wire showed that the unloading stress was 30-50% of the loading stress, which was considered to be clinically important.

Traditional terminology used to describe the tensile properties of orthodontic wires was not sufficient to describe the unusual properties of the superelastic Ni-Ti wires. The new parameters that were considered clinically important were the pseudoplastic range (PPR), the stress required for the start of the phase transformation, measured at the pseudo-0.1% yield strength and the maximum elastic elongation, measured at 0.1% yield strength.

Further research is needed to enable the prediction of the unloading bending behaviour from test tensile data. This association should enable the orthodontist to use the tensile test data to predict the behaviour of superelastic Ni-Ti wires clinically.

Chapter 1

Introduction

The behaviour of a material, when subjected to forces, is of fundamental importance to orthodontists, since all orthodontic archwires must withstand applied forces without fracturing. Furthermore, orthodontic archwires must behave elastically. An 'elastic' property infers that an appliance deforms when it is loaded but returns to its original shape when the force is removed, i.e., an appliance must be used within its elastic limit so that permanent deformation will not occur during use (Van Vlack 1970, Eisenstadt 1971).

Elastic behaviour is the linear relationship between force and deformation, and the tensile test is the most common way of investigating this property (Hayden, Moffatt and Wulff 1965; Davis, Troxell and Hauk 1982; Nikolai, Anderson and Messersmith 1988). The test, which usually takes several minutes to achieve fracture point, provides various useful parameters with which we can communicate on wire properties.

Since most wire studies have been directed to bending behaviour, classic parameters such as the elastic modulus, the 0.1% yield strength, the elastic elongation, the ultimate tensile strength and the elongation at fracture are not available for all orthodontic wires. Therefore, these parameters are not often used when communicating about orthodontic wires. The establishment of useful parameters by conducting the tensile test on orthodontic wires is required.

The property claimed to be 'superelasticity' was introduced into dentistry when Andreasen and Hilleman (1971) adopted a nickel titanium (Ni-Ti) wire, Nitinol, for orthodontic use. New tensile parameters were needed as well as the classical tensile properties to describe and compare these superelastic wires. This knowledge is particularly important in relation to their clinical requirements.

Much of the current information on orthodontic wires is based on clinical experience and the advice of their manufacturers. Furthermore, little comparative information is available for currently marketed Ni-Ti wires.

Tensile testing of Ni-Ti wires at ambient temperature was appropriate to begin this study, but testing was also carried out at mouth temperature, since the behaviour of superelastic Ni-Ti wires was claimed to be temperature dependent (Burstone, Qin and Morton 1985; Burstone 1994).

Chapter 2

Aims and Objectives

The aim of this study was to compare commercially available orthodontic Ni-Ti wires by assessing their tensile properties at ambient and mouth temperatures. In order to make the comparison clinically relevant, the traditional tensile parameters were critically examined and new tensile parameters were introduced where necessary. Variations among superelastic wires at the same temperature, and variations with the same wire between ambient and mouth temperatures were identified.

The parameters commonly determined by the tensile test and any such parameters available for orthodontics wires were first reviewed. The literature on the development and testing of Ni-Ti wires was also reviewed, so that experimental results of the present study could be adequately interpreted.

Chapter 3

Review of the Literature

3.1 Tensile test of orthodontic wires

Testing a material to fracture in tension gives parameters such as elastic modulus, yield strength, elastic elongation, elongation at fracture, and ultimate tensile strength (UTS). The Standards Association of Australia (1977) recommended that the tensile test of wires be carried out at a crosshead speed of 0.5 ± 0.1 mm/min for five samples. The length of the test wire between the grips should be at least 50 mm and the average diameter of the wire recorded to the nearest 0.001 mm. The Standards Association of Australia (1977) determined only the ultimate tensile strength (UTS) and classified the wires into six groups by this property (minimum 1720 MPa).

On the other hand, bending tests simulate the manner in which orthodontic wires are clinically used. In fact, the American Dental Association Specification No. 32 for stainless steel orthodontic wires, as described by the Council on Materials and Devices (1977), is a cantilever bending test. Many researchers have gathered bending test data (Miura *et al.* 1986; Schaus and Nikolai 1986; Nikolai *et al.* 1988; Kapila and Sachdeva 1989; Lipshatz, Brockhurst and West 1992). The determination of bending properties will be the subject of a subsequent study.

A paucity of tensile test information existed for Ni-Ti orthodontic wires, as indicated by the number of published studies (Watanabe 1982; Miura *et al.* 1986).

Among the available tensile data, the results given by Watanabe (1982) in Table 3.1 compare stainless steel wires, a cobalt chromium (Co-Cr) wire, Nitinol and a superelastic Ni-Ti wire, Sentalloy. As shown in this table, values for elastic modulus, UTS and elongation at fracture are tensile properties found for some orthodontic wires. The only tensile parameter prescribed by the Standards Association of Australia (1977) was UTS, values for which were available for stainless steel and Co-Cr orthodontic wires but not for the superelastic Ni-Ti wires.

Gold alloys, routinely used for orthodontics wires prior to the 1950s, disappeared from orthodontic use in the 1960s (Kusy and Greenberg 1981; Proffit 1993). As a result, their tensile properties are difficult to find in the literature.

Table 3.1 Tensile properties from a study by Watanabe (1982).

Wire	Elastic Modulus (GPa)	U.T.S. (MPa)	Elong. at Fracture (%)
S/S - A	167-196	2286	1.2-1.6
S/S - B	#	1784	#
Co-Cr	196-225	1470-1813	2.4-3
Nitinol	49-59	#	6
Superelastic Ni-Ti	78	#	11

S/S stainless steel, # not given.

Ample tensile data are available for stainless orthodontic wires which reflects the extensive research carried out for stainless steel in general. This material was developed by Brearley of Sheffield in 1913 and was commercially available in either austenitic or martensitic form (Friel 1934). Martensite was named after a German metallurgist Adolf Martens, who noticed that austenitic stainless steel developed an extremely fine lattice structure when quenched from a high temperature. This structure was named martensite (Shimizu and Tadaki 1987).

Martensitic transformation, originally observed by cooling, could be described as a 'domino-like' distortion of an alloy's lattice structure, which brings the alloy's atoms closer to each other, without the relocation of atomic bonds (Kousbroek 1984; Shimizu and Tadaki 1987; Porter and Easterling 1992).

Three early austenitic stainless steel brands with different chromium-nickel contents were Firth's "Staybrite" (18% Cr, 8% Ni, 0.1% C), Brown Bailey's "Anka" (15-16% Cr, 10-11% Ni), and Krupps' "Wipla" (20% Cr, 7% Ni). In 1929 Friel introduced the 18-8 "Staybrite" stainless steel into orthodontics (Friel 1934). The American Iron and Steel Institute has developed a series numbering system, which placed the austenitic stainless steels in the 300 series. The types 302 and 304 make up the 18-8 group of stainless steels used in orthodontics (Thurow 1982).

3.2 Nickel titanium orthodontic wires and superelasticity

A nickel titanium (Ni-Ti) alloy was developed as Nitinol (an acronym for Nickel Titanium Naval Ordnance Laboratory) by Buehler in the early 1960s (Andreasen and

Morrow 1978). The composition of the thermal memory Nitinol was 55% nickel and 45% titanium (Andreasen, Bigelow and Andrews 1979). Nitinol was described as having shape memory or thermoelasticity. That is, after being deformed while in its martensitic phase, it returned to its original shape when its temperature was raised through its transition temperature range (TTR) by completely inducing its austenitic phase at 37°C (Andreasen and Morrow 1978). Miura *et al* (1986) and Yoneyama *et al.* (1992) have since disclaimed the shape memory and superelastic properties of Nitinol. Superelastic Ni-Ti wires such as Japanese Ni-Ti have been tested at 37°C, as they are claimed to have their TTR near mouth temperature (Miura *et al.* 1986; Yoneyama *et al.* 1992; Lipshatz *et al.* 1992).

The phase change from martensite to austenite occurred at relatively low temperatures for Ni-Ti when compared with other alloys, which have transition temperatures at hundreds of degrees Centigrade (Shimizu and Tadaki 1987). Nitinol, which was the Ni-Ti originally marketed in the 1970s in a stabilised martensite phase (M-NiTi), did not exhibit phase transition effects. Proffit (1993) and Burstone (1994) stated that Nitinol was strong, had poor 'formability', but had excellent 'springiness' with at least twice the elastic range of stainless steel prior to permanent deformation.

Austenitic Ni-Ti (A-NiTi) which was developed by the Furukawa Electric Company in Japan, was marketed in the 1980s as Sentalloy or Japanese Ni-Ti (Miura *et al.* 1986). Also in the 1980s, Chinese Ni-Ti wire, another A-NiTi was developed by Dr. Tien Hua Cheng and associates (Mohlin *et al.* 1991). This wire was tested by Burstone *et al.* (1985). A-NiTi showed an unusual load/deflection curve due to stress induced phase change when warmed above its TTR, which was thought by Proffit (1993) to be near ambient temperature. Proffit (1993) reported that these superelastic A-NiTi wires showed excellent properties for use as initial aligning arch-wires and generally replaced M-NiTi wires for this purpose. The M-NiTi wires were then recommended for use as rectangular wires in the later stages of orthodontic treatment.

3.2.1 Superelasticity and shape memory

Symbols adopted for this study which are commonly used in describing phase transformations of A-NiTi during heating and cooling are illustrated in Figure 3.2 and are listed below:

- A_s Start of austenitic transformation on heating.
- A_f Finish of austenitic transformation on heating.
- M_s Start of martensitic transformation on cooling.
- M_f Finish of martensitic transformation on cooling.
- M_d Temperature above which the martensitic form cannot be stress induced from its austenitic form (Duerig and Pelton 1994).
- TTR Temperature transition range on heating.

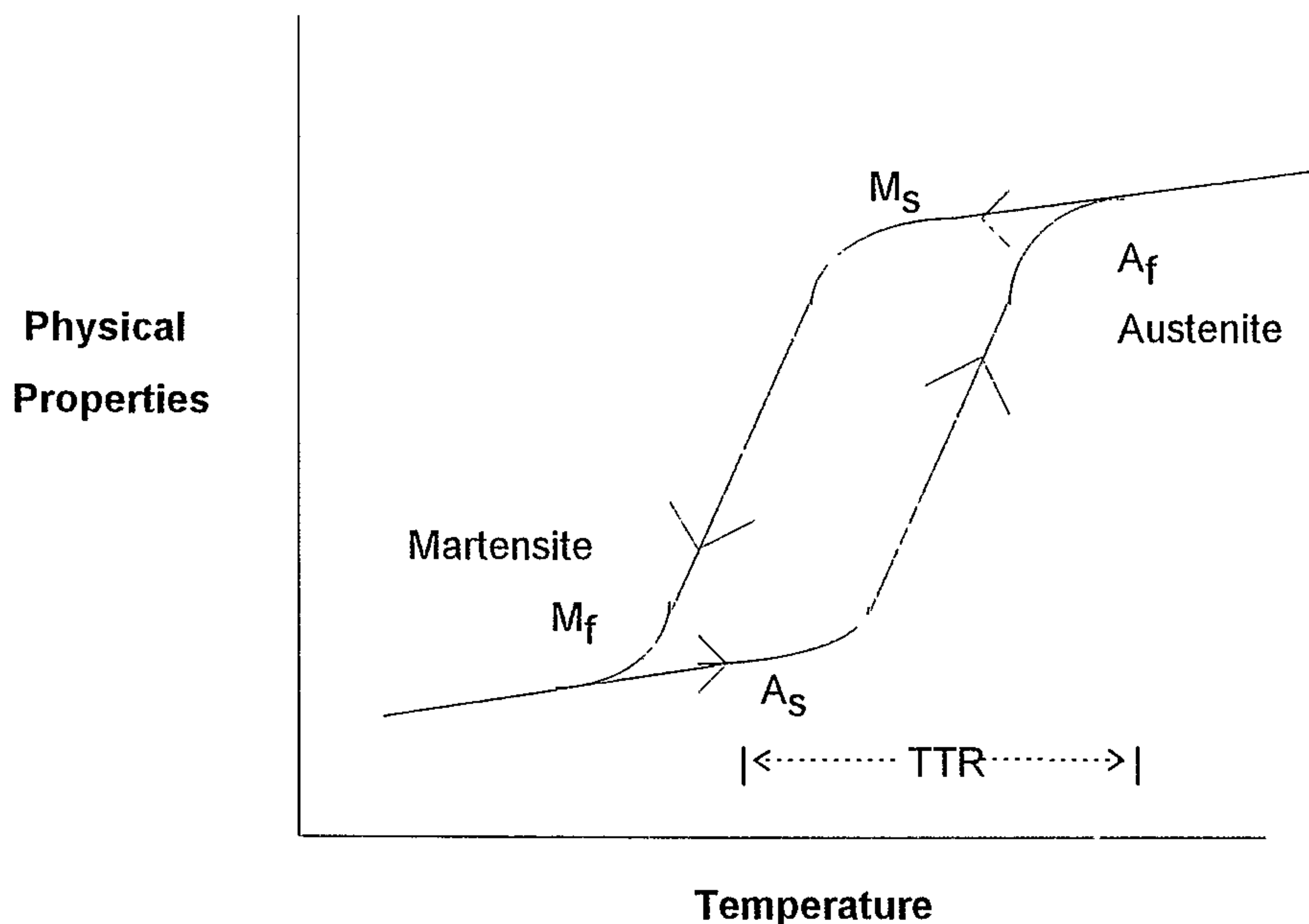


Figure 3.1 Thermally induced martensitic transformation of a superelastic Ni-Ti wire showing the martensitic transformation on cooling from M_s to M_f and reverse transformation back to the austenitic phase on heating from A_s to A_f (Duerig and Pelton 1994).

Although a superelastic Ni-Ti wire has been claimed to be a shape memory wire, these two properties are different. Superelasticity for Ni-Ti wires refers to high elasticity, due to a seemingly plastic (pseudoplastic) deformation of A-NiTi which completely recovers after removal of the load. This pseudoplasticity is due to the parent austenitic phase transforming to the stress induced martensitic phase when loaded. However, shape memory is the property of an A-NiTi wire which, after being deformed in its martensitic phase, allows the wire to return to its original shape by heating it through

its temperature transition range (TTR). Superelasticity (pseudoplasticity) is stress induced and is the mechanical analogue of the thermally induced shape memory effect. Kousbroek (1984) claimed that pseudoplasticity and shape memory effect were complementary. That is, if one property is small, the other is large. Both states involve transformations between the austenitic and martensitic phases.

The terms pseudoplasticity and pseudoelasticity have been used to describe superelasticity. Kapila, Haugen and Watanabe (1992) used the term pseudoplasticity to describe the effect of loading a superelastic wire, and pseudoelasticity to describe the wire when unloading. Delaey *et al.* (1974) and Kousbroek (1984) used the single term pseudoelasticity to describe the unusual loading and unloading stress/strain phenomenon. The term pseudoplasticity, but not the term pseudoelasticity, was used in the present study, because seemingly plastic but unusually 'real' elastic deformations were observed with these superelastic Ni-Ti wires.

Hamanaka *et al.* (1989) investigated mechanical properties, especially the super-elastic characteristics of twenty commercial orthodontic Ni-Ti alloy wires. These investigators devised two parameters from the load-deflection curve, the superelastic index (SEI) for superelasticity, and the E-load for the load in the superelastic region. The SEI was calculated as $(1-K_3/K_4) \times 100$, where K_3 was the slope at the end of the unloading plateau and K_4 was the final unloading linear slope. The E-load was the load at the end of the unloading plateau (at A_f). Therefore the E-load indicated the orthodontic load by the wire on the teeth. Yoneyama *et al.* (1989) assessed that the SEI for the best superelastic wires was above 70, while the SEI for Nitinol, which showed a nearly linear load/deflection curve, was below 30. The E-load is more clinically useful than the SEI, but neither parameter indicated the length of the plateau, which is also clinically important.

Two main types of martensitic transformation exist, i.e., thermally induced and stress induced (Shimizu and Tadaki 1987). These transformations are described in more detail in the following sections.

3.2.2 Thermally induced martensite and shape memory

Kousbroek (1984) reported that the thermoelastic transformation was originally observed in a Cu-Zn alloy by Greninger and Mooradian in 1938.

Thermally induced martensite forms gradually as the temperature drops, and disappears as the temperature rises. The growth rate of austenite (A_s to A_f) on heating and martensite (M_s to M_f) on cooling is dependent upon the rate of change of

temperature. The thermally induced martensitic transformation behaviour is often termed thermoelasticity (Delaey *et al.* 1974; Kousbroek 1984).

Andreasen, Heilman and Krell (1985) described an alloy with this 'thermodynamic' property as a shape memory alloy, which 'remembered' its previous shape when heated through its transition temperature range (TTR). Kousbroek (1984) claimed that a shape memory alloy could remember its shape partially or completely, depending on the amount of initial deformation.

Miura *et al.* (1986) stated that at a low temperature the close-packed hexagonal lattice (cph) of the Japanese Ni-Ti martensite is ductile and easily deformed, but at a high temperature the body-centred cubic lattice (bcc) structure of austenite is more difficult to deform. Kusy (1990) agreed with these interpretations of the crystal structures.

The TTR of a Ni-Ti wire was dependent on the ratio of nickel to titanium in the alloy and the method of processing. It could also be altered by substituting cobalt for nickel (Andreasen, Wass and Chan 1985).

Jardine, Field and Herman (1991) reported that on cooling a Ni-Ti alloy from the parent austenitic phase to below M_s , this alloy can form an intermediate rhombohedral phase (R-phase), prior to the face-centred tetragonal martensitic (fct) phase. Khier, Brantley and Fournelle (1991) using differential scanning calorimetry (DSC) thermograms, also found an extra exothermic peak corresponding to this R-phase. However, Yoneyama *et al.* (1992) found an extra endothermic DSC peak when heating from A_s - A_f , which they thought corresponded to the R-phase.

Two types of shape memory effect potentially occur, one-way shape memory and two-way shape memory. However, currently only the one-way shape memory effect is possible for orthodontic Ni-Ti wires, i.e., the alloy does not change shape again on cooling (Kousbroek 1984).

3.2.2.1 One-way shape memory—A fully thermally induced martensitic form at the start of deformation can be reshaped by reorientation upon applying an external stress. If the shape memory alloy is stressed at a constant temperature, enough to cause thermodynamically stable plastic deformation, subsequent heating will cause the alloy to regain its original shape. The martensite completely changes to austenite at A_f and a strain of 6-8% can completely recover. One-way shape memory alloys do not subsequently change shape again on cooling (Kousbroek 1984).

3.2.2.2 Two-way shape memory—Two-way shape memory occurs when an alloy specimen remembers the original shape on heating and also the deformed shape on cooling. This phenomenon is a result of reversible residual strain, and upon cooling

below M_s the material begins to remember its deformed shape (Kousbroek 1984). Stroz, Kwarciak and Morawiec (1988) suggested that two-way shape memory with Ni-Ti alloys can be produced by introducing fine particles which are insoluble during martensitic transformation on heating. However, two-way shape memory is not a current property of orthodontic Ni-Ti wires.

3.2.3 Stress induced martensite and pseudoplasticity

Stress induced martensitic transformation is the mechanical analogue to thermally induced martensitic transformation, and pseudoplasticity is the mechanical analogue to the thermally induced shape memory effect (Kousbroek 1984).

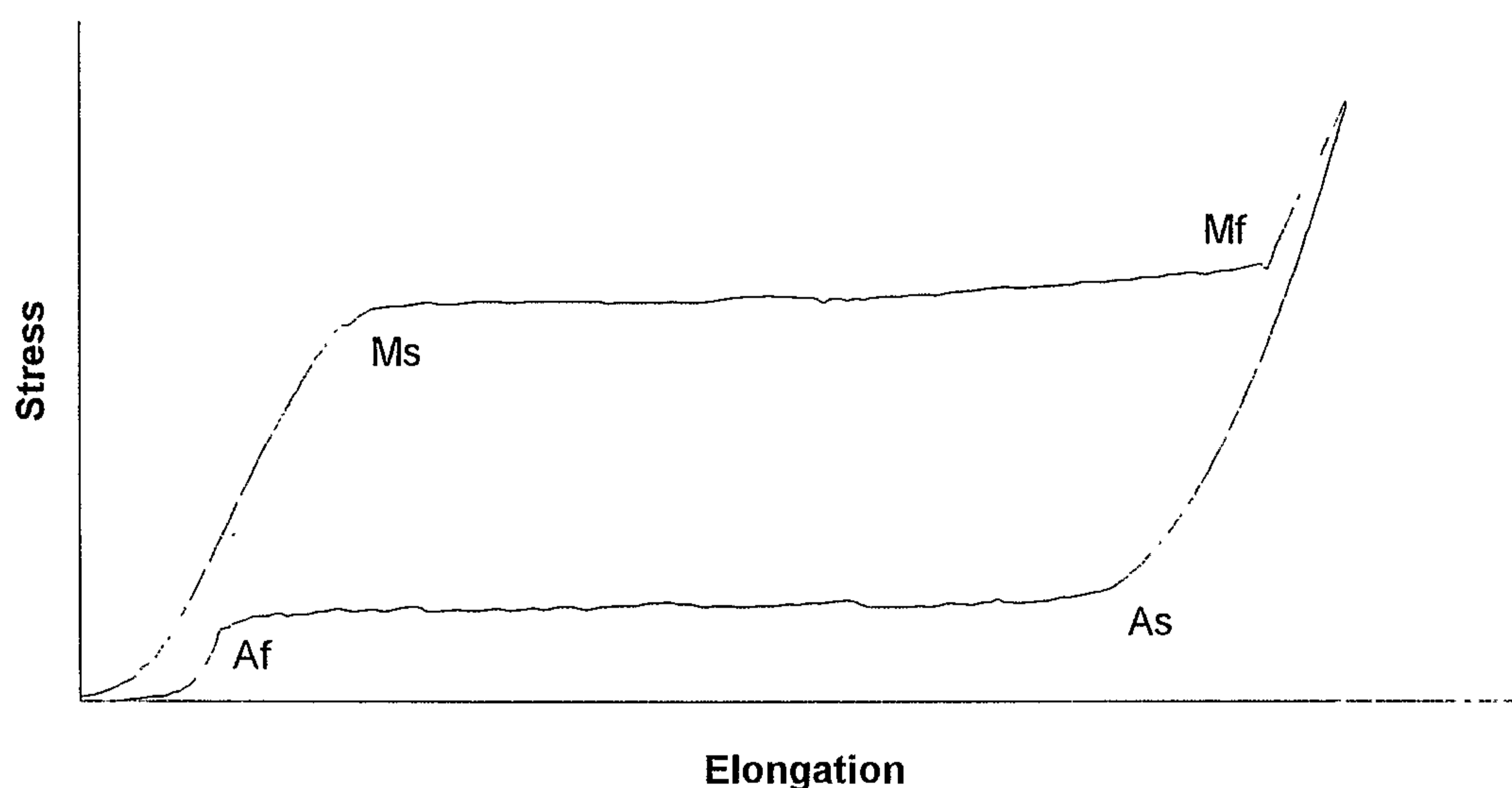


Figure 3.2 Stress induced martensitic transformation of a superelastic Ni-Ti wire indicated by the loading pseudoplastic plateau from M_s to M_f and reverse transformation back to the austenitic phase indicated by the unloading pseudoplastic plateau from A_s to A_f (Kousbroek 1984).

Pseudoplasticity by transformation to the martensitic phase occurs when stressing the austenitic phase above the temperature for A_s , but below a temperature limit, M_d (Kousbroek 1984; Duerig and Pelton 1994). However, if the temperature is less than that needed for A_f , the stress induced martensite remains essentially stable on unloading (Kousbroek 1984).

Andreasen, Wass and Chan (1985) described superelasticity as the ability to spring back to its original shape after being released from a gentle bend. Superelasticity, due to distinct pseudoplasticity in Ni-Ti wires, was attributed to wires which exhibited flat load/deflection curves on loading and unloading (Miura *et al.* 1986).

At a low temperature the close-packed hexagonal lattice (cph) of the martensite was ductile and was easily deformed, and at a high temperature Japanese Ni-Ti has the body-centred cubic lattice (bcc) of austenite which was more difficult to deform. Deformation in most metals caused slippage in the lattice structure, but deformation of Japanese Ni-Ti caused martensitic transformation from its parent austenitic phase (Miura *et al.* 1986).

Superelasticity is a desired property in an orthodontic wire as it delivers a relatively constant force over a relatively large deflection (Miura *et al.* 1986).

3.3 Other testing methods for orthodontic wires

Bending and torsional tests, differential thermal analysis, dynamic mechanical analysis and X-ray diffractometry have also been used for the evaluation of the mechanical properties of orthodontic wires.

3.3.1 Bending tests—The cantilever bending test, specified by the Council on Materials and Devices (1977), was also a traditional method for determining stress/strain properties and was used by Burstone and Goldberg (1983). This test was found to be inappropriate for very flexible wires as an increase in wire length and reduction of contact angle from 90° during testing significantly decreased the test load/deflection ratio. Such a test resulted in the plotted curves of flexible non-superelastic wires falsely indicating pseudoplasticity (Miura *et al.* 1986). Khier *et al.* (1991) used 6 mm lengths of test wire with the cantilever bending to reduce the problems when testing wires for superelasticity. These investigators suggested that theoretically the tensile stress/strain curve could be derived from the cantilever moment-angular deflection curve.

Miura *et al.* (1986) used a three-point bending test to determine the clinical value of the wires, as they believed that the traditional cantilever test was inappropriate to test for superelasticity. Variations have been introduced with the three-point bending test. Mohlin *et al.* (1991) used the three-point bending test with and without the wires tied into the brackets. Kapila *et al.* (1991) used a three-point bending test and also ligated the wires into the brackets.

Nikolai *et al.* (1988) introduced a five-point bending test and evaluated it as a replacement for the cantilever bending test. These investigators considered that this alternative bending test had merit over the cantilever bending test, but they did not support their case by discussing its advantages over the three and four-point bending tests.

Asgharnia and Brantley (1986) researched bending and tensile test methods for orthodontic wires and found that the elastic modulus and the yield strength when measured using the three-point bending test was much higher than that shown by a tensile test. This result was apparently due to the bending causing the outer portion of the wire to undergo work-hardening through permanent deformation. The tensile test, however stressed the wire uniformly.

Lipshatz *et al.* (1992) used the three-point bending test, without the wires tied into the brackets, to test Japanese Ni-Ti, Nitinol and braided Ni-Ti at 37°C and 24°C. These investigators found that the unloading force of Japanese Ni-Ti at 24°C was less than at 37°C.

3.3.2 Torsional tests—Andreasen and Morrow (1978) used a static torsional test to compare stainless steel wire with Nitinol, concluding that Nitinol exhibited a lower torsional moment than stainless steel. Drake *et al.* (1982), examining torsional properties found that Ni-Ti wires displayed approximately one quarter of the 'spring rate' (stiffness) of stainless steel and about half that of titanium-molybdenum-alloy (TMA).

Kapila and Sachdeva (1989) suggested that tensile, bending and torsion tests, although they may not emulate the clinical circumstances, gave good indicators for comparison of various wires. Tensile tests measured the yield strength, the elastic modulus, the stored energy (resiliency) and the springback. Bending tests measured bending moments against angular deflection, and clinically reflected bending for first and second order movements. Torsional tests measured torsional moments against torque angle, and clinically reflected torquing ability.

3.3.3 Differential thermal analysis—Differential thermal analysis (DTA) has been used by Kwarciak, Lekston, and Morawiec (1987), Lee *et al.* (1988) and Yoneyama *et al.* (1992) to measure the phase transformation temperatures of superelastic Ni-Ti wires and the thermal energies needed for these transformations. However, the latter two groups of researchers used the term differential scanning calorimetry (DSC) to describe DTA.

A typical DSC curve for a superelastic Ni-Ti wire was shown to have two endothermic peaks on heating, with one peak due to the rhomboidal phase transition and the second peak due to reverse transformation to the austenitic phase (Yoneyama *et al.* 1992). These researchers found a smaller exothermic peak on cooling that was due to transformation to the martensitic phase. They also found that most Ni-Ti wires required the temperature for A_f to be between 17°C and 32°C and that definite endothermic peaks were required for superelasticity.

3.3.4 Dynamic mechanical analysis—The dynamic mechanical analysis (DMA) has been used by Kusy and Wilson (1990) to simultaneously measure phase transitions, thermal expansion coefficients and elastic moduli. The DMA used the ‘Autovibron’ which had a signal generator to actuate the driver to cycle the wire sample at a specified frequency. The system analysed the stress/strain relationship by recording the resultant out-of-synchronised stress response to an imposed sinusoidal strain on the wire while raising the temperature.

3.3.5 X-ray diffractometry—X-ray diffractometry has been used by Kwarciak *et al.* (1987) and Matsumoto and Ojima (1989) to assess phase transformation of Ni-Ti wires. Kwarciak *et al.* (1987) performed a phase analysis of the Ni-Ti alloy ingots using a ‘...Philips diffractometer with a high temperature X-ray camera...’ for assessing the phase changes during heating and cooling. These investigators found that cycling caused reductions in phase transformation temperatures. They also reported that cycling of the alloy containing the Ti_2Ni phase caused its precipitation, which could destabilise the alloy.

The paucity of tensile test data for orthodontic Ni-Ti wires lead to the present study. This comparative study of commercially available orthodontic Ni-Ti wires was conducted at ambient and mouth temperatures to examine these wires at clinically applicable temperatures. Traditional tensile parameters were examined and new tensile parameters were introduced.

Chapter 4

Materials and Methods

4.1 Materials

Eight Ni-Ti orthodontic wires tested in the present study are listed, together with manufacturers' names, batch numbers and codes, in Table 4.1. The table also has a stainless steel wire included for comparative purposes. The nominal diameter of all wires was 0.406 mm.

Table 4.1. Wires tested in the present study.

Wire Type	Name / Description	Manufacturer	Batch Number	Code
Stainless Steel	Premium Plus	Wilcock	KH.RKK	SS
Ni-Ti	Nitinol	3M Unitek	053 & 304	NT
	CX Enterprise	Unknown	Not given	CX
	'Genuine' Chinese	ORSU	Ni 040	OR
	Sentalloy (medium)	GAC	D1013	SA
	Rematitan Lite	Dentaurum	71744	RL
	NiTi	Ormco	3K133K	OM
	Reflex	TP	382-116	TP
	Super-elastic	3M Unitek	502	SE

One of the Ni-Ti wires was Nitinol, which was introduced as the first of this type of alloy in the early 1960s. Two Chinese-origin Ni-Ti wires were tested. The manufacturer of CX Enterprise was unknown, while the second wire was supplied by Professor Jiu-Xiang Lin of the Beijing Medical University. The latter was manufactured at the Beijing ORSU Medical Equipment Company and was claimed by Professor Lin to be genuine Chinese Ni-Ti orthodontic wire. Sentalloy and Rematitan Lite were of Japanese and German origin, respectively. The remaining three wires, NiTi, Reflex and Superelastic were of U.S.A. origin.

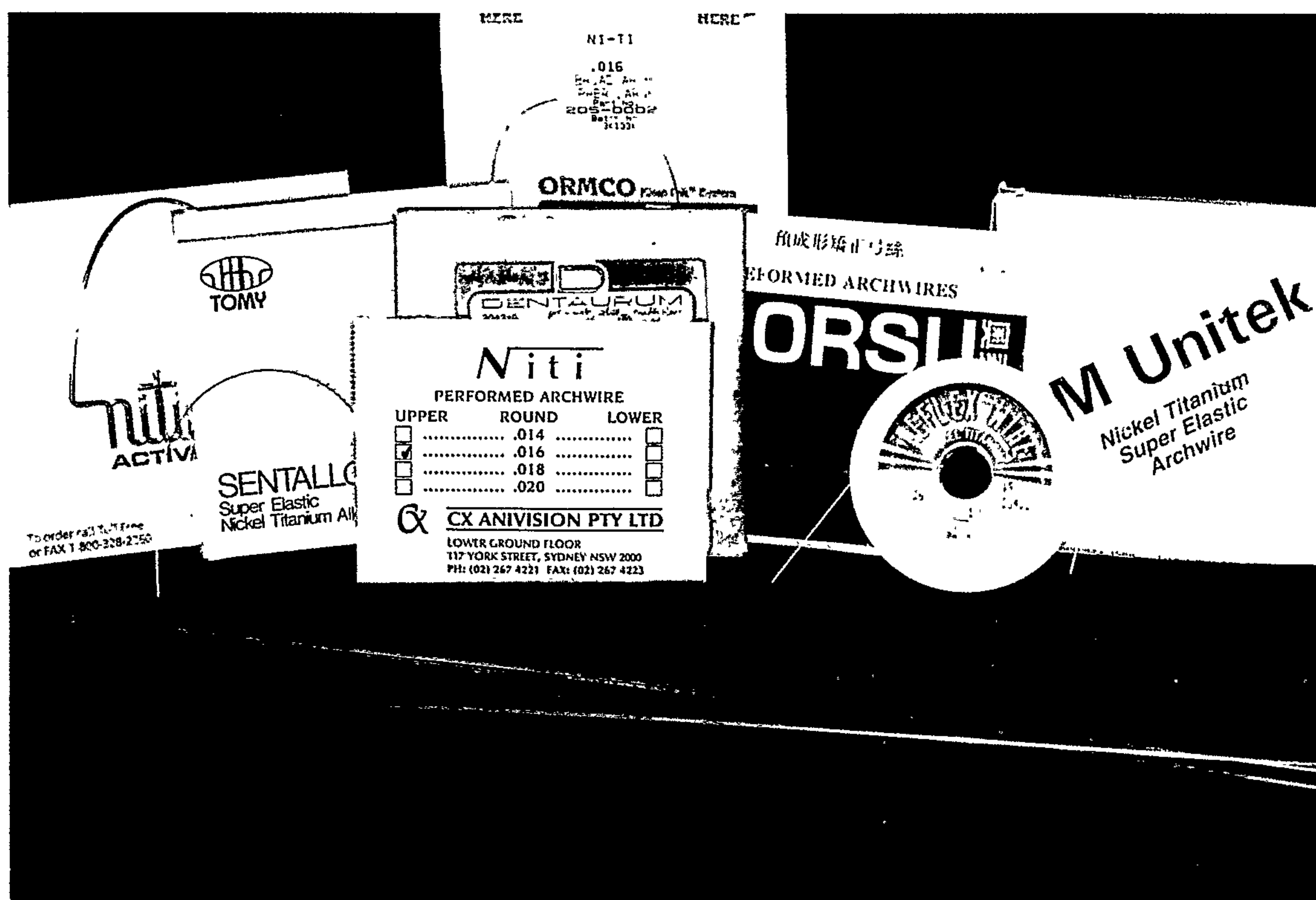


Figure 4.1 Ni-Ti wires used in this study.

4.2 The tensile test

Each wire was supplied from the manufacturer in preformed arch shapes except for OR, RL and TP. The preformed wires were straightened by hand prior to testing, as recommended by the British Standards Institution (1976). Each specimen's diameter was measured at six different locations using a micrometer (Moore and Wright 965B, Sheffield, England) to an accuracy of 0.001 mm and the average was calculated for each.

Figure 4.2 shows a universal testing machine (Autograph AG-50NE, Shimadzu, Kyoto, Japan) used for testing the wires.

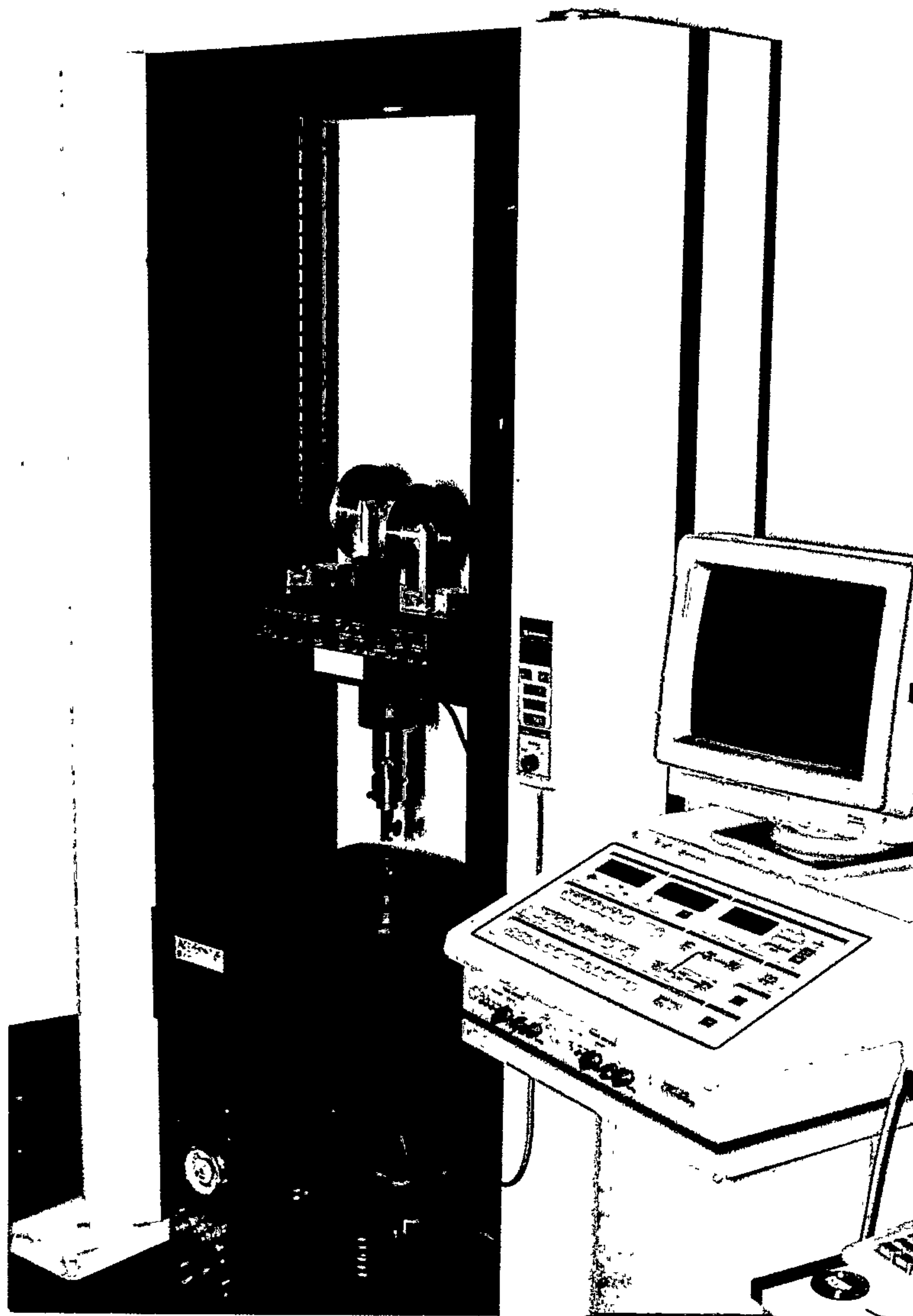


Figure 4.2 The universal testing machine (Shimadzu, Autograph AG-50NE).

Each specimen was cut to a length of approximately 80 mm, allowing a test length of 50 mm between the grips as recommended by the Standards Association of Australia (1977) and shown in Figure 4.3. The grips had soft round metal inserts which were regularly sand-blasted to prevent slippage of the wires. To ensure that the correct test length was employed, the inter-grip distance was checked with a custom made metal rod gauge.

At least five specimens of each wire, as recommended by the Standards Association of Australia (1977), were tested at $23^{\circ}\text{C} \pm 1^{\circ}$, and at $37^{\circ}\text{C} \pm 0.5^{\circ}$. An initial load of 0.5 N (50 g) was used to eliminate slack in the wires, as recommended by the British

Standards Institution (1976), especially for the wires which were supplied in curved archforms.

The stainless steel wire was tested at a crosshead speed of 0.5 mm/min and at ambient temperature, as recommended by Standards Association of Australia (1977). Some of the Ni-Ti wires were initially tested at a crosshead speed of 0.5 mm/min at ambient temperature, but subsequently tested at a crosshead speed of 1 mm/min. This latter speed proved more practical for Ni-Ti wires.

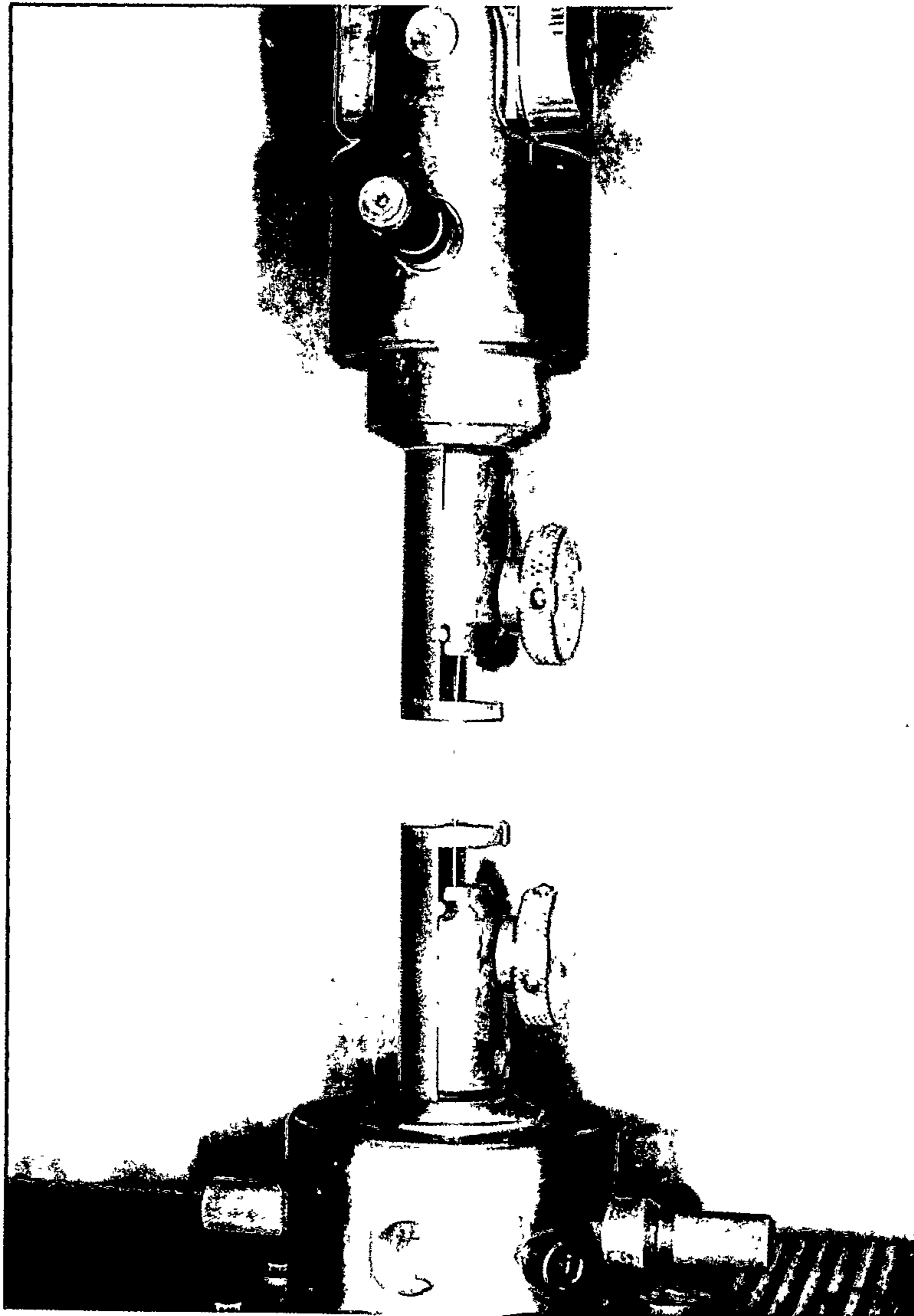


Figure 4.3 Steel grips for holding the test wires.

The Ni-Ti wires were also tensile tested at 37°C. For this test, a temperature controlling water bath was placed around the lower jig (Figure 4.4). The top was open to allow the placement of a copper coil through which water, at a thermostatically controlled temperature, was circulated from a controller (Thermo-Circulator, Churchill, Instrument Co., Perivale, England). The top of the wire was totally immersed in the water. However, due to the design of the bath, a portion of the wire

near the lower grip was not in the water. The temperature of the water was controlled within 1°C of the target temperature and measured using a Type K thermocouple (Therma 1, Duff and McIntosh, Sydney).

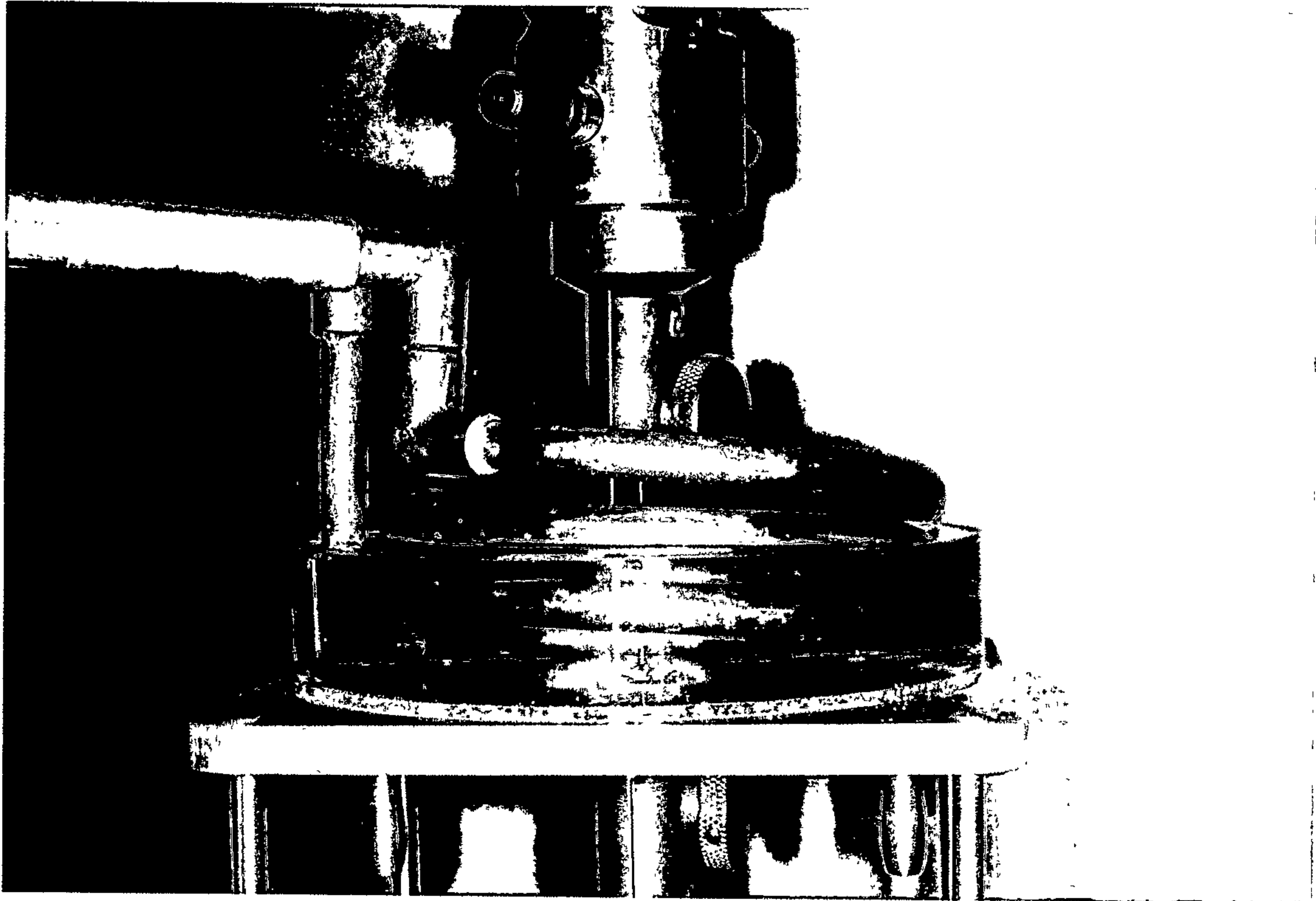


Figure 4.4 Temperature control arrangement within the water bath, showing the copper coil through which water flowed at a thermostatically controlled temperature.

4.3 Statistics

A completely randomised design analysis of variance was conducted by the F-test as a 2×7 factorial design. Only variables with $F < 0.05$ were significant.

The Tukey's HSD (*honestly significant difference*) test was used to rank the means of the parameters of all Ni-Ti wires and in comparing the differences between the first and second slopes for the superelastic Ni-Ti wires.

The paired t-test was used to determine whether the means of first and second elastic moduli are different at ambient and at mouth temperatures.

Chapter 5

Results

5.1 Tensile properties at ambient temperature

Figure 5.1 shows four representative stress/strain curves of the wires tested at ambient temperature. Only SS and NT showed the appearance of classic stress/strain behaviour where the initial linear relationship between stress and strain was followed by plastic deformation and then fracture. The remaining seven wires exhibited unusual stress/strain curves in which yielding was shown by flattening of the curve. The flattening prolonged to form a plateau and then transformed into a second linear stress/strain relationship often showing a sharp kink at the transition.

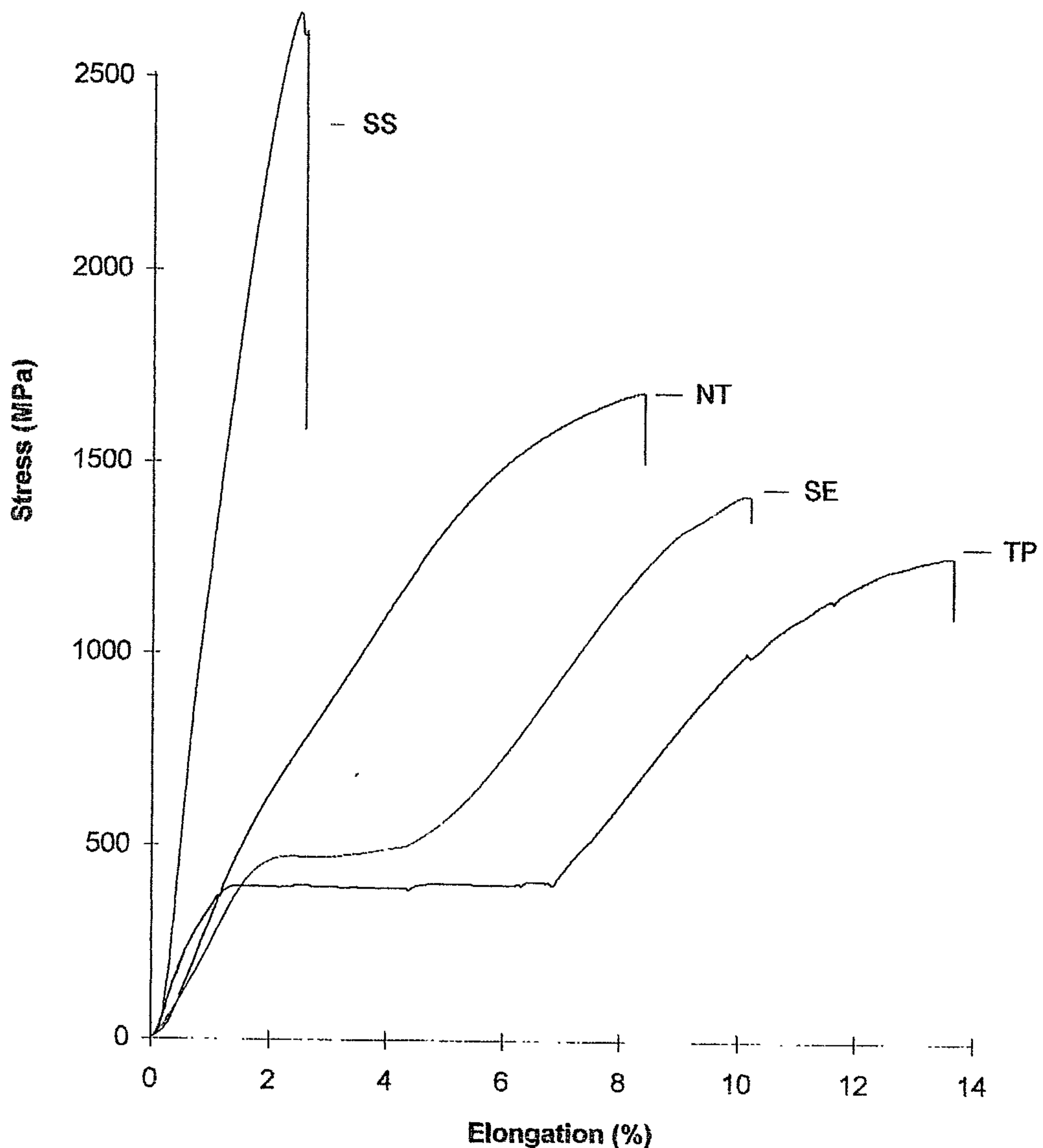


Figure 5.1 Representative stress/strain curves of four wires at ambient temperature, showing a stainless steel wire (SS), a non-superelastic wire (NT) and two superelastic Ni-Ti wires (SE & TP).

The appearance of the second linear stress/strain relationship implied that the first yield point was pseudo-yielding and the plateau was pseudoplasticity. Four tensile parameters are shown in Table 5.1. For all Ni-Ti wires except NT, the elastic modulus was calculated from the first slope before the pseudo-yielding and the second slope after the pseudoplasticity. These values are listed in Table 5.2.

The pseudo-0.1% yield strength (YS) observed with the seven Ni-Ti wires was used as a parameter to estimate the stress required for the martensitic transition (Section 3.2.3), and listed later in Table 5.1.

The average 0.1% YS, illustrated in Figure 5.2, and ultimate tensile strength (UTS) of SS at ambient temperature were 1777 MPa and 2593 MPa and much higher than those of all the Ni-Ti wires. The elongation at fracture of SS was only 2.5%, while that of the Ni-Ti wires was 7.5% (NT) at minimum and 13.1% (SA) at maximum. The elongations at fracture for NT, CX, OM, TP and SE at 37°C were significantly different to those at 23°C.

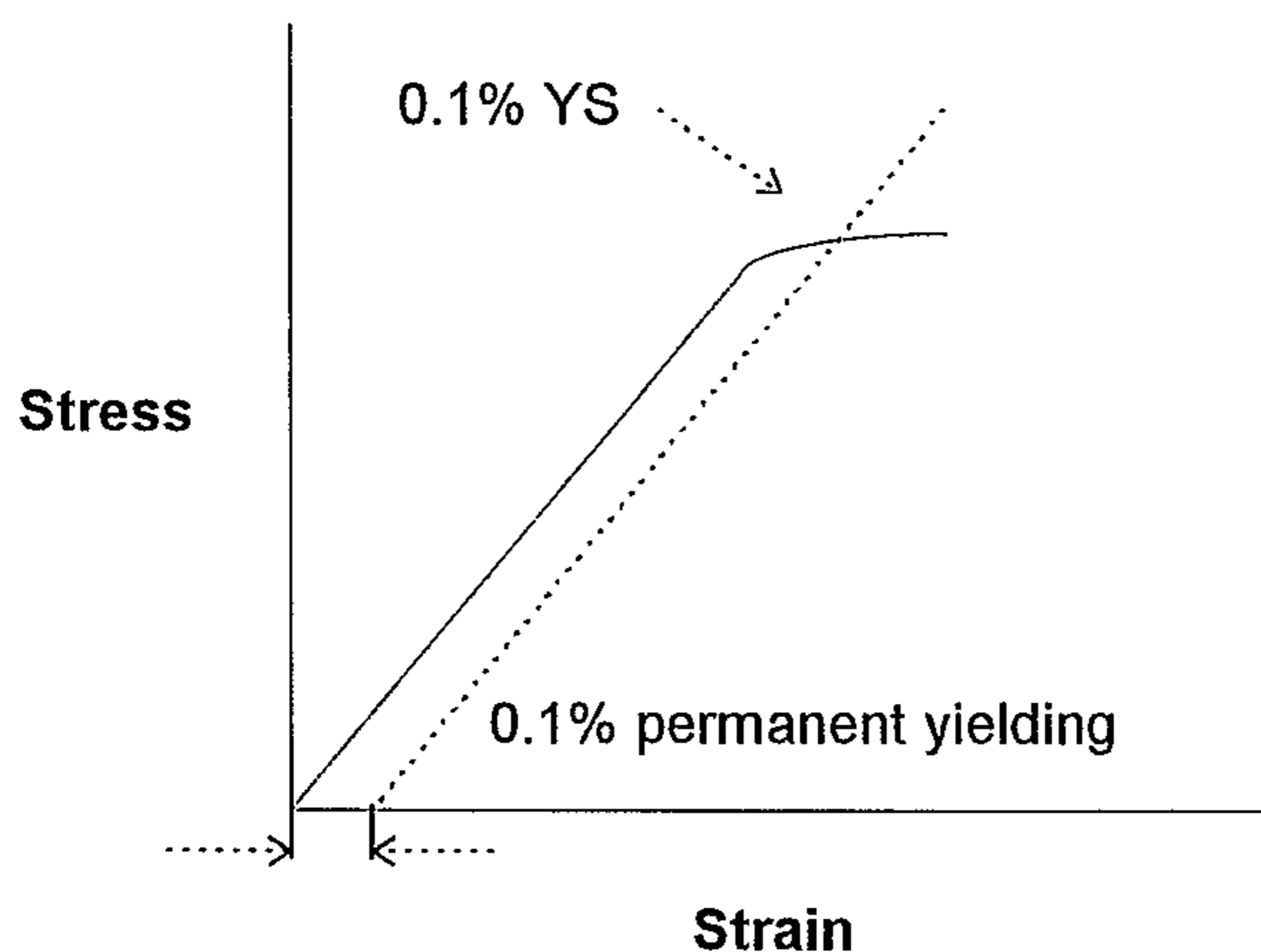


Figure 5.2 Classical linear stress/strain curve illustrating 0.1% YS corresponding to 0.1% permanent yielding, shown by the dotted line parallel to the linear slope projected back to the x-axis.

Nitinol did not show distinct pseudoplasticity at either ambient or mouth temperatures and was not displayed in further graphs with the superelastic wires, in this study. The superelastic Ni-Ti wires were considered to be the more important part of this study and seven are shown graphically as stress/strain curves in Figure 5.3 (ambient temperature) and Figure 5.4 (mouth temperature).

The 0.1% pseudo-yielding represents the stress required to start the martensitic transformation and was termed σ_{Ms} . All seven wires showed distinct pseudoplasticity (flattening) but exhibited different σ_{Ms} values, as shown in Table 5.4. The onset and end of the transformation also varied and these were denoted by M_s and M_f , respectively. The elongation related to the transformation process was expressed as the difference in strain at M_s and M_f , and was called the pseudoplastic range (PPR). These values are shown in Table 5.5.

The new phase formed after the transformation exhibited its own stiffness as the second slope in the stress/strain curves. This true 0.1% YS was equivalent to the conventional elastic limit and indicated the start of permanent deformation of these wires. The elongation to this point was called the maximum elastic elongation (MEE). These unique superelastic properties are shown in Tables 5.1 (tensile properties), 5.2 (elastic moduli) 5.4 (transformation stress) and 5.5 (elongational properties).

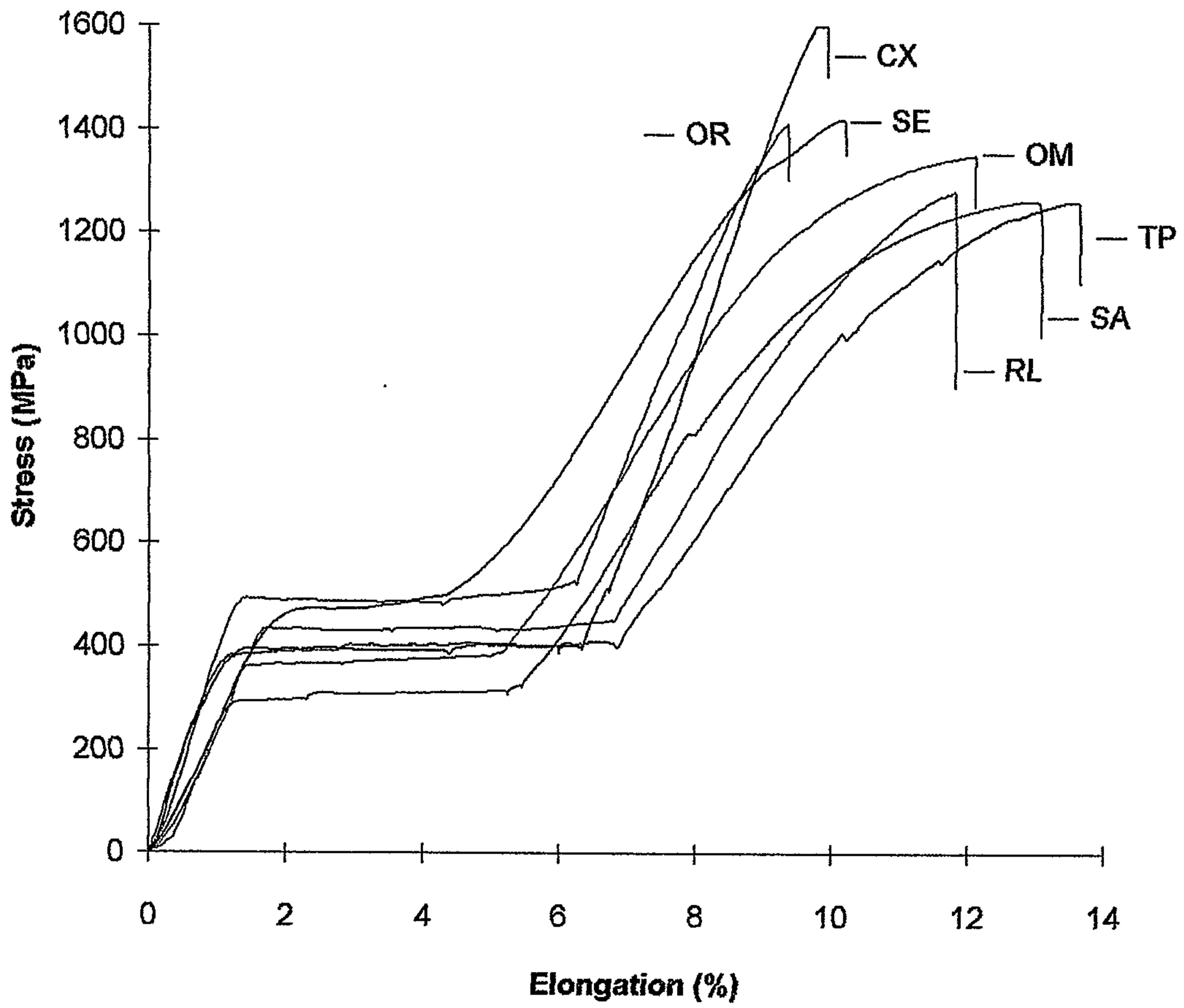


Figure 5.3 Superelastic Ni-Ti wires tensile tested at ambient temperature.

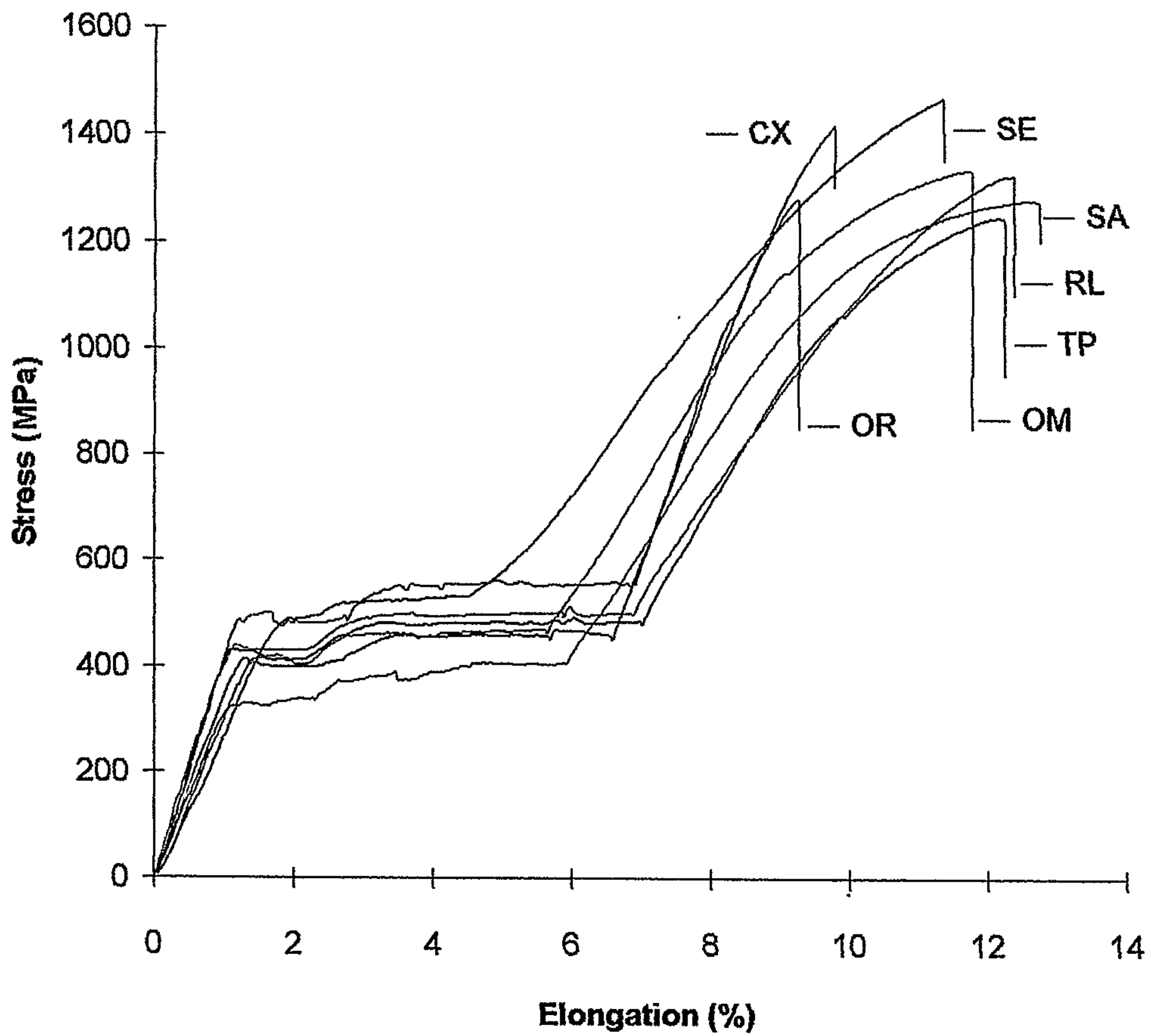


Figure 5.4 Superelastic Ni-Ti wires tensile tested at mouth temperature.

Table 5.1 Tensile properties at ambient and mouth temperatures.

Wire Code with Temperature		Pseudo 0.1% YS (MPa)	True 0.1% YS (MPa)	UTS (MPa)	Elongation at fracture (%)
SS	23°C	--	1777 (129)	2593 (113)	2.5 (0.4)
	37°C	--	#	#	#
NT	23°C	--	566 (18) d	1618 (47) a	7.5 (0.7) e
	37°C	--	652 (51.9) c	1753 (19) a	9.5 (0.5) c
CX	23°C	329 (17.9) d	1392 (103) a	1502 (42) b	9.7 (0.6) d
	37°C	408 (4.2) d	1167 (67) ab	1411 (21) b	9.8 (0.3) c
OR	23°C	489 (17.2) a	1294 (639) ab	1394 (40) cd	9.2 (0.2) d
	37°C	474 (6.9) a	1239 (101) a	1305 (92) cd	9.5 (0.4) c
SA	23°C	296 (4.3) e	942 (68) c	1248 (27) f	13.1 (0.5) a
	37°C	328 (8.9) e	961 (27) b	1264 (17) cd	12.6 (0.3) a
RL	23°C	433 (2.5) b	1024 (37) c	1276 (8) ef	12.0 (0.2) b
	37°C	439 (6.4) b	1010 (56) b	1323 (10) c	12.2 (0.3) a
OM	23°C	367 (6.9) c	1026 (62) c	1337 (13) de	12.4 (0.4) ab
	37°C	408 (6.5) d	1061 (38) b	1327 (14) c	11.8 (0.3) ab
TP	23°C	301 (11.0) f	1014 (35) c	1262 (24) f	13.0 (0.7) a
	37°C	425 (9.4) c	1002 (48) b	1244 (14) d	12.2 (0.3) a
SE	23°C	433 (2.1) b	1187 (66) b	1421 (7) c	10.5 (0.2) c
	37°C	461 (7.8) a	1198 (92) ab	1476 (19) b	11.1 (0.3) b

denotes not tested at this temperature

() denotes standard deviation

a,b,...e denotes l.s.d. statistical ranking for each tensile property at 23°C

a,b,...f denotes l.s.d. statistical ranking for each tensile property at 37°C

5.2 Elastic modulus—The elastic modulus (stiffness) has long been regarded as a major criterion in the selection of orthodontic wires, especially for stainless steel wires. Results of the present study showed that the elastic modulus value for SS (152 GPa) was much higher than the values for all of the tested Ni-Ti wires. The average elastic modulus value for NT was 39 GPa.

The elastic modulus of the first slope for the superelastic wires at ambient temperature (Table 5.2) was found to be the highest in OR (47 MPa) and TP followed in order by CX, OM, RL, SE and SA (27 MPa). The order was not the same at mouth temperature

and the values were significantly lower except for SA and RL, which were significantly higher, and TP and SE which were statistically similar.

Although the elastic modulus is less important in the selection of superelastic Ni-Ti wires, these wires have a second slope which indicated that the phase change has occurred and this elastic modulus needs consideration. The second slope was different from the first for all except CX at ambient temperature (t-test). The rest were all reduced from the first slope, except for CX at mouth temperature, which increased (Table 5.2).

Table 5.2 Elastic moduli of first and second slopes at ambient and mouth temperatures.

Wire Code with Temperature	1 st slope Elastic Modulus (GPa)	2 nd slope Elastic Modulus (GPa)	Different (P<0.05)
SS 23°C	152 (10.2)	--	--
37°C	#	--	--
NT 23°C	39 (0.7) b	--	--
37°C	37 (1.4) bc	--	--
CX 23°C	40 (1.2) b	41 (5.6) a	No
37°C	35 (1.8) bc	39 (0.8) a	Yes
OR 23°C	47 (2.6) a	37 (3.7) a	Yes
37°C	44 (2.2) a	34 (0.8) b	Yes
SA 23°C	27 (2.2) d	20 (1.8) b	Yes
37°C	31 (0.9) c	22 (0.2) c	Yes
RL 23°C	30 (0.9) d	22 (1.8) b	Yes
37°C	41 (0.9) a	21 (1.6) c	Yes
OM 23°C	34 (1.1) c	21 (0.8) b	Yes
37°C	31 (1.2) c	22 (0.7) c	Yes
TP 23°C	45 (4.9) a	19 (0.9) b	Yes
37°C	43 (1.9) a	23 (0.8) c	Yes
SE 23°C	30 (0.2) d	21 (0.3) b	Yes
37°C	31 (1.3) c	20 (0.5) c	Yes

denotes not tested at this temperature

() denotes standard deviation

a,b,...e denotes l.s.d. statistical ranking for each tensile property at 23°C

a,b,...e denotes l.s.d. statistical ranking for each tensile property at 37°C

The new parameters used in the present study are summarised in the following list:

Table 5.3 New tensile parameters for Ni-Ti orthodontic wires used in the present study.

Abreviation	Definition	Measuremen
σ_{Ms}	Martensitic transformation stress 'pseudo'-0.1% YS.	MPa
E_2	Second slope elastic modulus.	GPa
ϵ_{Ms}	Elongation at the start of the martensitic transformation which was indicated by the point on the curve for the 'pseudo'-0.1% YS.	% of the initial test length
ϵ_{Mf}	Elongation at the finish of the martensitic transformation, which was indicated by the point at the plateau end.	% of the initial test length
PPR	Pseudoplastic range or the length of the plateau ($\epsilon_{Mf} - \epsilon_{Ms}$).	% of the initial test length
MEE	Maximum elastic elongation measured at 0.1% YS.	% of the initial test length

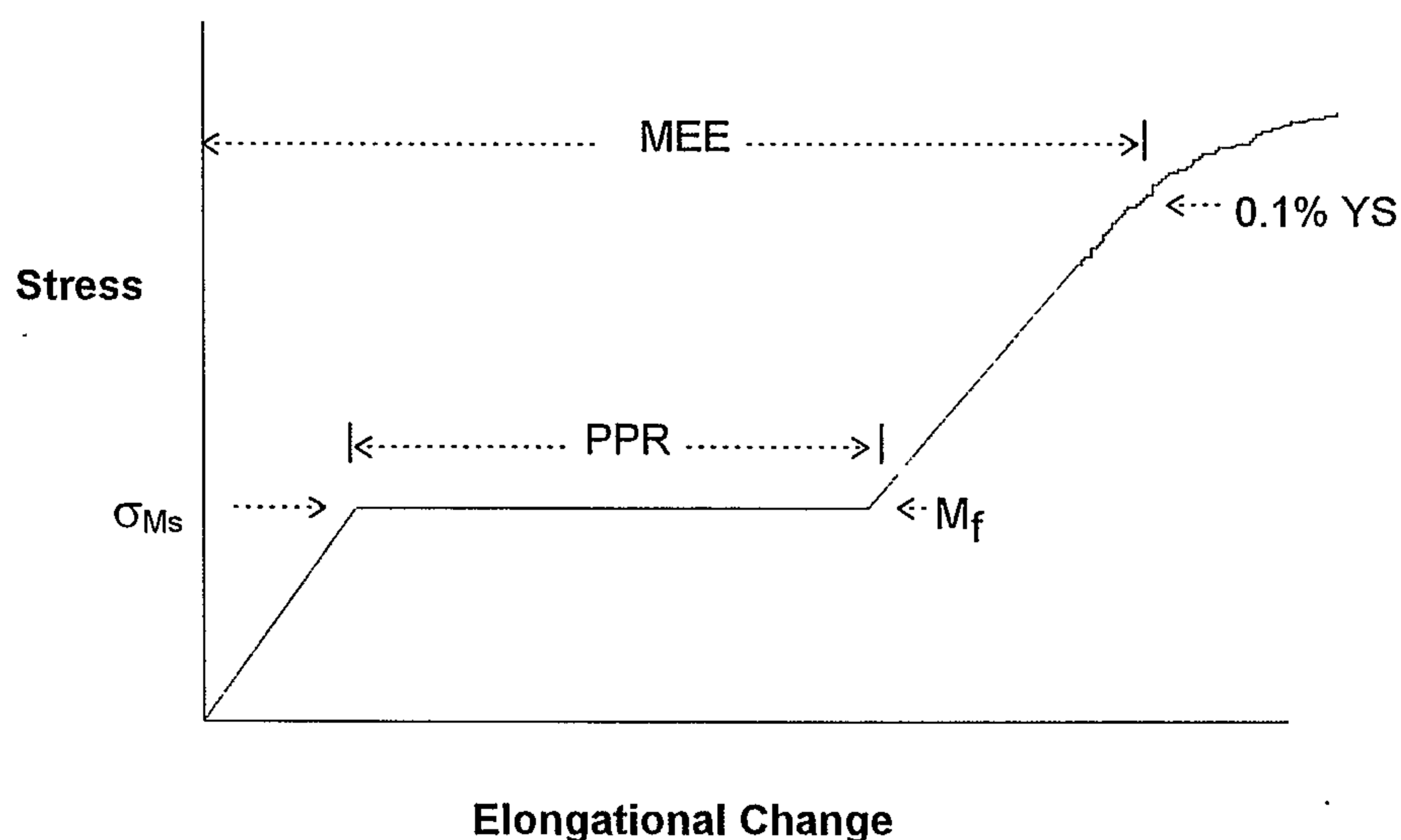


Figure 5.5 Stress/strain curve of a typical superelastic Ni-Ti wire showing σ_{Ms} , PPR and MEE.

5.3 Temperature effect on transformation stress (σ_{Ms})—The effect of temperature on the transformation stress of the superelastic wires is shown in Table 5.4. The transformation stress of all wires increased except for OR which decreased by 15 MPa and RL which was statistically unchanged.

Table 5.4 Comparison of transformation stress (σ_{Ms}) or pseudo-0.1% YS at 23°C and 37°C.

Wire Code	σ_{Ms} at 23°C (MPa)	σ_{Ms} at 37°C (MPa)	σ_{Ms} Difference between Temperatures.
CX	329 (17.9) d	408 (4.2) d	79
OR	489 (17.1) a	474 (6.9) a	-15
SA	296 (4.3) e	328 (8.9) e	32
RL	433 (2.5) b	439 (6.4) b	6*
OM	367 (6.9) c	408 (6.5) d	41
TP	301 (11.0) e	425 (9.4) c	124
SE	433 (2.1) b	461 (7.8) a	28

-ve σ_{Ms} for 37°C less than for 23°C
 () standard deviation
 a,b,...e l.s.d. statistical ranking
 * $P > 0.05$

The increase for the other wires ranged from 28 MPa for SE to 124 MPa for TP. An increase may indicate a thermally induced austenitic phase change between 23°C and 37°C (Section 3.2.2), prior to stress being applied.

5.4 Elongational properties of the superelastic wires

Exceptional elongation was the dominating feature of the superelastic Ni-Ti wires as shown in Table 5.5.

The stress required for the start of martensitic transformation (σ_{Ms}) at ambient temperature (Table 5.4), was found to be the highest in OR (489 MPa), followed in order by RL, SE, OM, CX, TP, and SA (296 MPa). The order was not the same at mouth temperature and also the σ_{Ms} values were significantly higher except for ORSU which was significantly lower. RL showed no significant change.

The elongation at the start of martensitic transformation (ϵ_{Ms}) at ambient temperature (Table 5.5), was highest in RL and SE (1.8%), followed in order by OM, OR, SA, CX and TP (0.8%). The order was not the same at mouth temperature and also the ϵ_{Ms} values for OM, OR and SE were significantly lower than their ambient temperature values. TP was significantly higher.

The elongation at the finish of martensitic transformation (ϵ_{Mf}) at ambient temperature (Table 5.5), was highest in RL and TP (6.9%), followed in order by OR, CX, SA, OM and SE (4.3%). The order was the same at mouth temperature, and the ϵ_{Mf} values were statistically similar to their ambient temperature values.

The pseudoplastic range $\epsilon_{Mf}-\epsilon_{Ms}$ (PPR) at ambient temperature (Table 5.5), was found to be the highest in TP (6.1%), followed in order by CX, RL, OR, SA, OM and SE (2.6%). The order was not the same at mouth temperature and also, the PPR values were significantly higher than their ambient temperature values in all except CX and TP.

The maximum elastic elongation (MEE) at ambient temperature, measured at the true 0.1% YS (Table 5.5), was found to be the highest in TP (10.1%), followed in order by RL, CX, SA, OR, OM, and SE (8.3%). The order was not the same at mouth temperature, but these MEE values were similar to their ambient temperature values in all except CX and TP, which were significantly lower.

Watanabe (1982) reported that Sentalloy tensile tested at mouth temperature had a 2% ϵ_{Ms} and 5% ϵ_{Mf} i.e., 3% PPR. The present study showed 1.2% ϵ_{Ms} and 6.0% ϵ_{Mf} , i.e., 4.8% PPR. Stress/strain plots reported by Watanabe (1982) showed indistinct changes for Sentalloy wire at M_s and M_f , whereas the Figures 5.2 and 5.3 in present study showed distinct changes at M_s and M_f for Sentalloy, as well as all other superelastic Ni-Ti wires, except SE.

Table 5.5 Elongational properties of superelastic Ni-Ti wires at ambient and mouth temperatures.

Wire Code and Temperature		Elongation (%)			
		ϵ_{Ms} (at M_s)	ϵ_{Mf} (at M_f)	PPR ($\epsilon_{Mf} - \epsilon_{Ms}$)	MEE (at true 0.1% YS)
CX	23°C	1.0 (0.1) c	6.3 (0.1) b	5.3 (0.1) b	9.0 (0.6) a
	37°C	1.3 (0.0) b	6.6 (0.1) b	5.3 (0.0) d	8.6 (0.2) b
OR	23°C	1.4 (0.2) b	6.3 (0.1) b	4.9 (0.1) c	8.6 (0.3) c
	37°C	1.3 (0.1) b	6.8 (0.5) b	5.5 (0.5) bc	8.9 (0.2) ab
SA	23°C	1.3 (0.1) b	5.4 (0.1) c	4.1 (0.1) d	8.9 (0.7) bc
	37°C	1.2 (0.1) b	6.0 (0.1) c	4.8 (0.1) d	8.7 (0.3) b
RL	23°C	1.8 (0.1) a	6.9 (0.1) a	5.1 (0.0) c	9.6 (0.3) ab
	37°C	1.2 (0.2) b	7.0 (0.2) a	5.7 (0.1) ab	9.5 (0.5) a
OM	23°C	1.5 (0.1) b	5.3 (0.1) c	3.8 (0.0) e	8.6 (0.4) c
	37°C	1.4 (0.1) b	5.6 (0.1) d	4.2 (0.1) e	8.5 (0.1) b
TP	23°C	0.8 (0.1) c	6.9 (0.1) a	6.1 (0.1) a	10.1 (0.2) a
	37°C	1.2 (0.1) b	7.2 (0.1) a	6.0 (0.1) a	9.5 (0.2) a
SE	23°C	1.8 (0.1) a	4.3 (0.1) d	2.6 (0.1) f	8.3 (0.3) c
	37°C	1.7 (0.0) a	4.4 (0.1) e	2.7 (0.1) f	8.4 (0.4) b

() denotes standard deviation

a,b,...f denotes l.s.d. statistical ranking for each tensile property at 23°C.

a,b,...g denotes l.s.d. statistical ranking for each tensile property at 37°C.

5.5 Diameter of wires—The Standards Association of Australia (1977) and the British Standards Institution (1976) recommended wire diameter tolerances of ± 0.010 mm and ± 0.012 mm, respectively. As the nominal diameter of the test wires was 0.406 mm, the only wire which was outside the Australian and British standards of tolerance was one specimen of CX having a diameter of 0.392 mm. CX was also the most inconsistent in diameter (0.392 mm to 0.410 mm). SA and OM had the most accurate diameters with the all of their specimens being within 0.002 mm of the nominal 0.406 mm. Kusy and Stush (1987) and Tonner and Waters (1994) reported that the diameters of their test wires were usually less than the nominal dimensions.

5.6 Statistics—The completely randomised analysis of variance resulted in $F < 0.0001$ for all variables. Appendix 3 shows the statistical analyses for all parameters.

Wilcock Premium Plus wire test values were so different to the Ni-Ti wires that statistical analyses were not required to establish these differences.

Chapter 6

Discussion

6.1 Stainless steel

The purpose of this study was to investigate the tensile properties of Ni-Ti orthodontic wires. A stainless steel wire, Wilcock Premium Plus was also included for comparison. In contrast to Ni-Ti wires which have been mostly studied by the bending test, stainless steel wires have been extensively tested by the tensile test (Section 3.1). Table 6.1 compares tensile properties reported for stainless steel wires.

Table 6.1 Comparison of tensile properties of stainless steel wires including those obtained in the present study.

Tensile Property	Ware and Masson (1975) Premium	Twelftree <i>et al.</i> (1977) Premium Plus	Present Study Premium Plus	Drake <i>et al.</i> (1982) Unitek Stainless Steel	Goldberg <i>et al.</i> (1977) Unitek Permchrome
Elastic Modulus (GPa)	180	174 (6)	152 (10)	145 (15)	156 (80)
0.1% YS (MPa)	2220	2830 (29)	1777 (150)	1170 (40)	1880 (150)
UTS (MPa)	3010	3070 (15)	2593 (113)		
Elongation at Fracture (%)	2.2		2.5 (0.4)		

The present study showed a lower elastic modulus, 0.1% YS and UTS for Wilcock stainless steel than those reported by Ware and Masson (1975), and Twelftree, Cocks and Sims (1977). These investigators used extensometers to measure the elastic modulus which could help to eliminate erroneous readings for the elastic modulus due to slippage in the grips. However, an extensometer is not the complete solution as found by Drake *et al.* (1982), who encountered slippage of the extensometer on the wire, and reverted to recording directly from the crossheads. Their results were relevant to the present study which used crosshead movement to record elongation.

Ware and Masson (1975) used small diameter wrap-around type grips and Drake *et al.* (1982) did not specify the type of grips that they used. However, the wrap-around type grips were not suitable in the present study, because these grips required longer wire lengths than were available in the preformed Ni-Ti archwires. Therefore, the steel grips with soft round metal inserts were used in the present study. The relatively

low UTS recorded in the present study indicated that the development of better grips is important for recording the UTS, as breakage of the wire near the grips was often encountered. Although, the recording of the behaviour of the wires near fracture point may have been inaccurate due to the grips used, the recording of behaviour of the wires within elastic limits was believed to be accurate.

The Standards Association of Australia (1977) classified stainless steel wires into six typings by their UTS (Table 6.2). Ware and Masson (1975) stated that these typings were based on the grades of Wilcock stainless steel wires, Regular, Regular Plus, Special, Special Plus, and Premium. Wilcock (1989) believed that the high yield strengths gave the Wilcock higher grade wires advantages over the other orthodontic stainless steel wires. Subsequently, the higher grades 'Premium Plus' and 'Supreme' have been developed.

Table 6.2 Comparison of Standards Association of Australia typings of stainless steel wires. A.J. Wilcock gradings and UTS results from the present and other studies of Wilcock wires.

Standards Association of Australia Typings	UTS (MPa)	Wilcock Gradings	Ware and Masson (1975) (Premium)	Twelftree <i>et al.</i> (1977) (Premium Plus)	Present Study (Premium Plus)
1	1720-2240	--	--	--	--
2	2241-2400	Regular	--	--	--
3	2401-2550	Regular Plus	--	--	--
4	2551-2700	Special	--	--	2593 (113)
5	2701-2860	Special Plus	--	--	--
6	2870-	Premium	3010	--	--
		Premium Plus	--	3070 (15)	--
		Supreme	--	--	--

() denotes standard deviation

Table 6-2 shows that the U.T.S. results from the present study and previous studies are not always in agreement with the Standards Association of Australia typings.

Thurrow (1982), and Davis *et al.* (1982) claimed that the elastic moduli for all grades of stainless steel are similar at approximately 200 GPa. However, Goldberg, Vanderby,

and Burstone (1977) believed that cold-drawing of wire caused a 20% reduction in the elastic modulus than the 200 GPa as stated for stainless steel in metallurgical texts. These investigators found that the elastic modulus was approximately 155 GPa for Unitek Permachrome, which is similar to the value (152 GPa) obtained for Wilcock Premium Plus in the present study. However, Craig (1993) stated that the elastic modulus of stainless steel wires in general was 134 GPa.

6.2 Nitinol wire

Nitinol, being the original Ni-Ti orthodontic wire, has been the subject of many studies. Nitinol was thought to have shape memory when heated through its temperature transition range (TTR) and also superelasticity (Andreasen and Morrow 1978; Andreasen *et al.* 1985).

Andreasen (1980) reported that Nitinol demonstrated the shape memory effect. This investigator bent his ideal archform in Nitinol and heat treated it to 450° C for 10 minutes. Considering that the TTR of Nitinol was 31°C to 45°C, this investigator reported on the orthodontic usage of this wire to complete arch alignment in 163 days. However, the elasticity of the wire and not shape memory was likely to have produced the arch alignment. The shape memory effect is due to a thermally induced phase change causing the wire to return to the pre-set shape after heating through the TTR, not the shape setting by heat treatment as indicated by Andreasen (1980).

However, Miura *et al.* (1986) described Nitinol as a work-hardened wire with neither shape-memory nor superelasticity, as a result of their tensile study at 37°C. This opinion was supported by Yoneyama *et al.* (1992) and Waters (1992) who stated that Nitinol had a stabilised martensitic structure, and that Nitinol did not have superelastic properties because of the amount of cold-working used for its manufacture. Furthermore, Yoneyama *et al.* (1992) found that Nitinol displayed no endothermic peak using differential scanning calorimetry (DSC).

Although the present study supported the view that Nitinol is not a superelastic wire, as it lacked the plateau on the stress/strain curve, it did show greater elasticity than expected from a typical linear stress/strain relationship.

Figure 6.1 shows hysteresis plots of different samples of Nitinol a, b and c which were elongated to 4%, 5% and 6%, respectively, during a preliminary cyclic investigation. Although the data showed significant permanent deformation at all three elongations, the elastic stress/strain relationship was not purely linear. This finding indicated that that Nitinol showed pseudoplasticity. Kusy and Stush (1987) believed that the elastic limit should be determined using cyclic loading tests and also found the loading elastic

moduli to be about 5% greater than the unloading elastic moduli. Further cyclic testing is needed to precisely determine the elastic limit of the Ni-Ti wires tested in the present study.

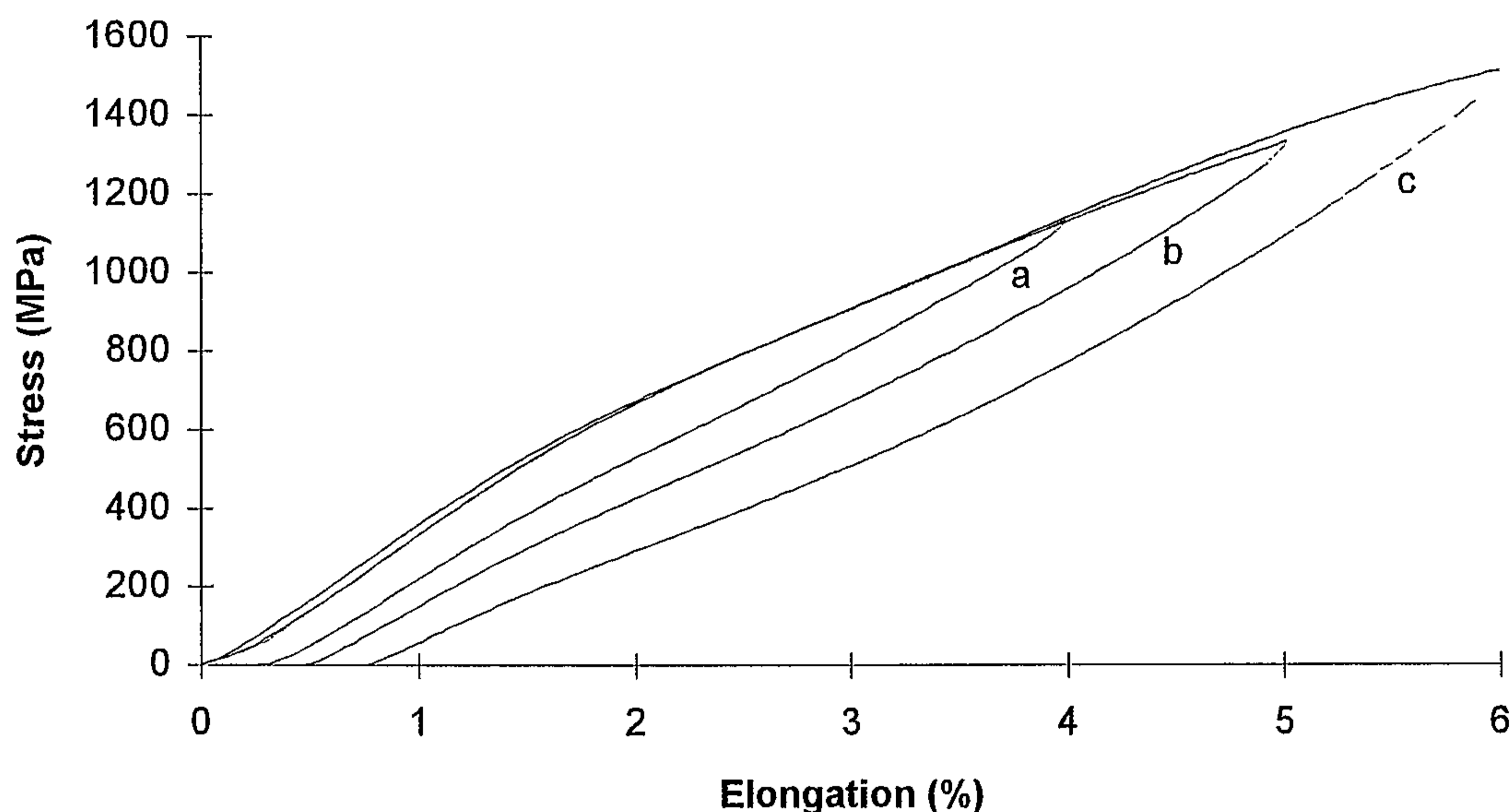


Figure 6.1 Different samples of Nitinol a, b and c elongated to 4%, 5% and 6% during cyclic tensile testing at mouth temperature, showing approximately 0.3%, 0.5% and 0.8% permanent yielding, respectively.

Kusy and Stush (1987) reported that the 0.1% YS for wires was traditionally believed to be approximately 75% of the UTS. However, their study showed that 1.0% YS for Nitinol corresponded to approximately 75% of its UTS. The 0.1% YS and the 0.2% YS corresponded to about 50% and 60% of the UTS respectively. The present study showed that 0.1% YS for Nitinol was 35 % of its UTS (Table 5.1). These findings indicated that the YS and the UTS were not as closely related as previously thought.

Table 6.3 Reported tensile properties for 0.4 mm diameter Nitinol wires.

Tensile Property	Drake <i>et al.</i> (1982) Nitinol	Watanabe (1982) Nitinol	Present Study Nitinol AT/MT ⁺⁺
Elastic Modulus (GPa)	34 (1)	49-59	39/37
0.1% YS (MPa)	340 (30)	#	566/652
Elongation at fracture (%)	#	#	7.5/9.5

++ AT/MT denotes ambient temperature/mouth temperature.

not given

Table 6.3 shows that Drake *et al.* (1982) found that Nitinol had a 0.1% YS of 340 MPa when tensile tested, which was much lower than the value of 566 MPa for Nitinol found in the present study at ambient temperature. Their reported elastic modulus for Nitinol was similar to that found in the present study, but Watanabe (1982) found a substantially higher value. These findings indicated that the value of the elastic modulus for Nitinol was uncertain.

Kusy and Stush (1987) found that round Nitinol had a higher elastic modulus than rectangular Nitinol, as measured with a bending test. These authors concluded that this result was due to cold working in the production of rectangular wires. Kusy and Stush (1987) used the following formula to determine the elastic modulus from bending test:

$E = PS/6I\delta$ —relating the elastic modulus to bending force (P), span index (S), moment of inertia (I) and corresponding beam deflection (δ).

Kusy and Stush (1987) and Unitek/3M (1989) claimed that Nitinol exerted a light constant force while returning to its original shape after deflection, without confirming that it was capable of distinct pseudoplasticity. The present study disagreed with their claim, as Nitinol showed no pseudoplastic plateau in the tensile test at either ambient or mouth temperatures.

Unitek/3M (1989) also claimed that Nitinol was 50% stiffer than Nitinol SE. The present study showed that Nitinol's elastic modulus (stiffness) was not higher than any of the superelastic Ni-Ti wires tested, including Nitinol SE. Therefore, Unitek/3M (1989) may have misinterpreted the definition of stiffness.

6.3 Superelastic nickel titanium orthodontic wires

All Ni-Ti wires except Nitinol showed superelastic properties, with Nitinol SE showing the lowest PPR for the superelastic Ni-Ti wires, having shown the shortest plateau in its stress/strain plot.

6.3.1 Before the stress induced phase change—The elastic modulus was not as clinically useful with superelastic Ni-Ti wires as it has traditionally been for conventional wires, with only one linear stress/strain slope. However, a high elastic modulus may be clinically useful for superelastic Ni-Ti wires, to enable the phase transformation to begin with a low deflection of the wire. The elastic moduli for these wires at ambient temperature varied from the stiffest ORSU Chinese Ni-Ti (47 MPa) to Sentalloy (27 MPa) as shown in Table 5.2. Rematitin Lite and Sentalloy showed significantly lower elastic moduli at ambient than at mouth temperature, which could have improved the ease of placement of the wire prior to warming to mouth temperature.

6.3.2 The phase change—The 0.1% YS was classically used to describe the onset of permanent deformation, but the present study has shown that the first ‘yield point’ for the superelastic wires was pseudo-yielding. The stress at this point was a good indicator for the stress required for the onset of martensitic phase change (σ_{Ms}).

A low σ_{Ms} could be clinically advantageous, by allowing the wire to enter into the pseudoplastic plateau at a low stress.

Manufacturers often supplied insufficient, or misleading, information on the properties of their materials. For example, Sentalloy, according to its manufacturer, GAC, had a transformation temperature at about 34°C, but the present study showed evidence of pseudoplasticity for this wire at ambient temperature (~23°C). This finding indicated that the start of the thermally induced phase transformation to austenite (A_s) occurred at a lower than ambient temperature and that the transformation temperature claimed by GAC was at the finish of this transformation (A_f).

Yoneyama *et al.* (1992), using differential scanning calorimetry (DSC), found the endothermic peak corresponding to A_f point to be 71°C for Nitinol SE which is well above body temperature. These investigators believed that this temperature for A_f was too high to show superelasticity even at mouth temperature.

6.3.3 After the phase change—The presence of a second slope, which has not previously been reported on, indicated that the stress induced martensitic phase change had occurred. The second slope indicated the elastic modulus of the martensitic phase. A low second slope elastic modulus could be advantageous, if the wire were clinically stressed beyond its PPR. However, the stress related to this steep second slope needs to be carefully considered if the Ni-Ti wire were stressed beyond the PPR, as the load on teeth may be physiologically too high.

The second slope was significantly reduced from the first slope for all superelastic Ni-Ti wires at ambient and mouth temperatures, except CX Enterprise Chinese Ni-Ti which increased at mouth temperature. TP Reflex Ni-Ti showed the greatest reduction of 26 GPa and 20 GPa at ambient and mouth temperatures, respectively (Table 5.2). Although statistically significant differences occurred between the two elastic moduli, the differences may not be clinically important.

The UTS and elongation at fracture are common engineering parameters, but have little clinical importance as orthodontic wires should not be stressed to the fracture. Elongation within the elastic limit is of more clinical value.

Duerig and Pelton (1994) used the term ‘free-recoverable strain’ for the maximum elastic elongation (MEE). These authors reported that the MEE was 8% for Ni-Ti

alloys, but should be limited to 6% to allow complete recovery. The present study used 0.1% YS as the indicator for the MEE which varied from approximately 2 % for Nitinol to 8-10% for the superelastic Ni-Ti wires (Table 5.3).

Figure 6.2 shows hysteresis plots from an additional investigation in the present study where unloading tensile properties were also measured for Nitinol (NT) and CX Enterprise Chinese Ni-Ti (CX). These Ni-Ti wires were elongated to 4% and 7% at mouth temperature respectively. The resulting permanent deformations were only 0.3% and 0.1% which support the premise that 0.1% YS is an important clinical parameter for orthodontists to compare the MEEs for orthodontic wires.

Also of note in Figure 6.2, was that the plateau on the unloading curve recorded approximately 30-50% of the stress that was recorded on the loading curve. This meant that when maintaining the stress within the pseudoplastic plateau, the stress by the superelastic Ni-Ti wire on the tooth would be 30-50% of the stress (σ_{Ms}) originally required to place the wire into the orthodontic brackets.

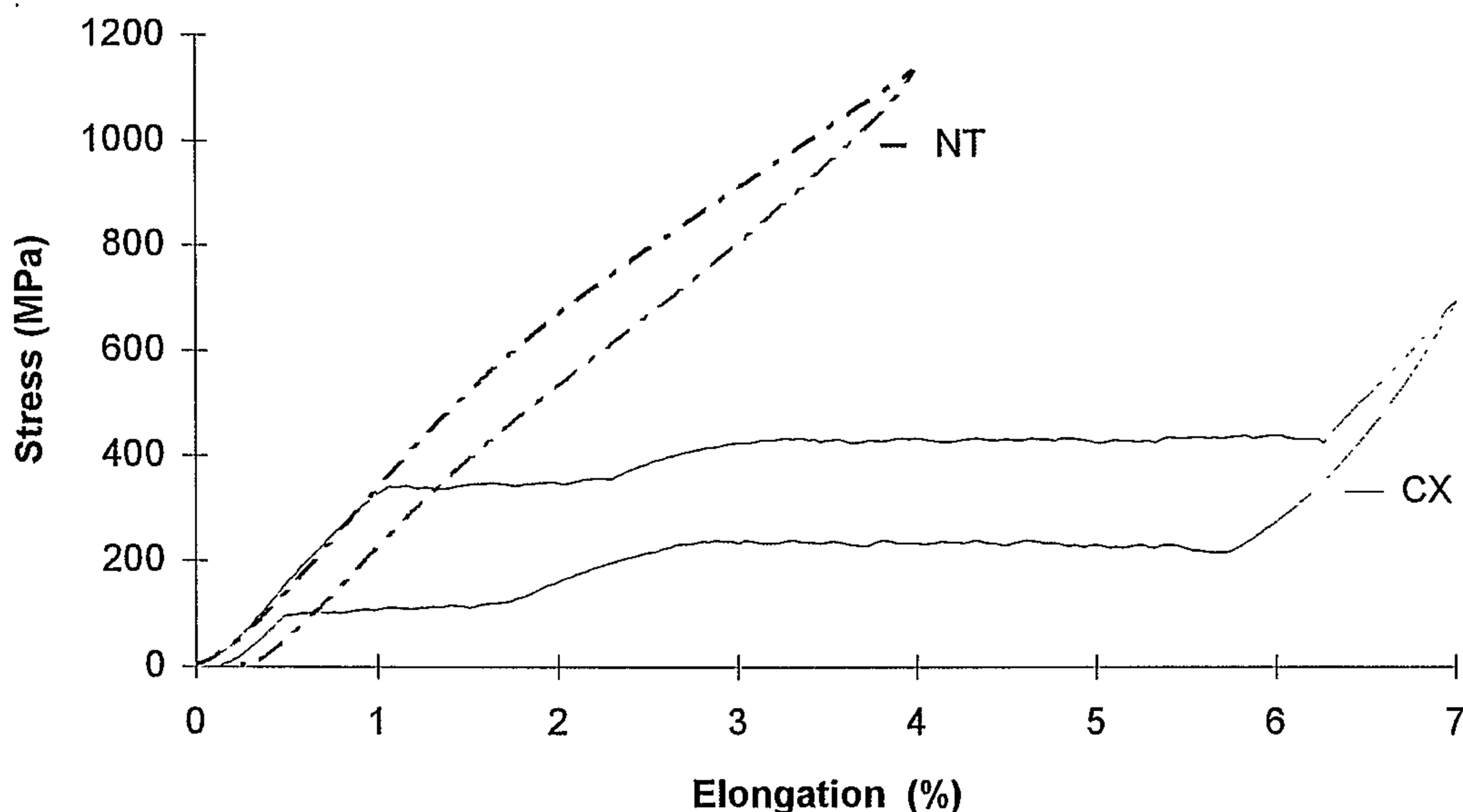


Figure 6.2 NT elongated to 4% and CX to 7% during cyclic tensile testing at mouth temperature, showing approximately 0.3% and 0.1% permanent yielding, respectively.

6.4 Load magnitude and tooth movement

The use of orthodontic wires is integral with the application of a load and associated tooth movement. The relationship between load and tooth movement has been the subject of investigation and debate, but no clear consensus has been reached (Quinn and Yoshikawa 1985). These authors reviewed key studies which examined the assumption that an optimal load existed for tooth movement.

Quinn and Yoshikawa (1985) addressed four hypotheses on the relationship between the rate of tooth movement and load:

1. Hypothesis 1 stated that a constant relationship existed between the rate of tooth movement and load. However, these authors found no studies that supported this assumption.
2. Hypothesis 2 stated that a continual linear relationship existed between the rate of tooth movement and load. However, these authors found no studies that supported this assumption.
3. Hypothesis 3 stated that a linear relationship existed between the rate of tooth movement and load until a maximum rate of movement, after which, the rate of movement declined. Smith and Storey (1952) supported this hypothesis.
4. Hypothesis 4 stated that a linear relationship existed between the rate of tooth movement and load until a maximum rate of movement occurred. Thereafter, the rate of movement did not noticeably increase with increased load. Evidence for this theory came from the studies of Hixon *et al.* (1969) and Boester and Johnston (1974) which showed evidence of a plateau at load values of 300 g and 140 g, respectively.

Therefore, the plateau theory of Hypothesis 4 was supported on the evidence of studies of Hixon *et al.* (1969) and Boester and Johnston (1974). These studies also claimed that tipping tooth movement was more likely to occur than pure bodily movement. However, the slope of the initial linear relationship and plateau load had not been determined. Quinn and Yoshikawa (1985) estimated from available data that the optimal retractive load for a canine was 100-200 g, or 70-140 gcm⁻².

Quinn and Yoshikawa (1985) suggested that should the plateau theory be correct, posterior anchorage could be optimised by increasing the surface area in the posterior anchorage unit and using continuous light loads. The development of superelastic Ni-Ti wires has aided the production of light continuous loads.

6.4.1 Other evidence for light loads being optimal—Other evidence for light loads being optimal come from Reitan and Rygh (1994) who suggested that loads greater than 60-70 g for tipping and 150 g for bodily movement caused hyalinisation. This was in agreement with Burstone and Grove (1961) who claimed that tipping occurred best at 50-70 g.

The use of superelastic Ni-Ti wires was supported in this context by Burstone *et al.* (1985) and Miura *et al.* (1986) who believed that light constant loads provided by the superelastic Ni-Ti wires were more conducive to tooth movement than heavy interrupted forces. However, O'Brien *et al.* (1990) while investigating the clinical effectiveness of a superelastic Ni-Ti wire, Titanol, and a non-superelastic Ni-Ti wire, Nitinol, found no significant difference in tooth movement over 35 days for 20 patients in each group. An explanation for the latter finding was given by Burstone *et al.* (1981) who speculated that the high loads produced undermining resorption after hyalinisation, which may have allowed catch-up movement.

During the orthodontic treatment of adults Reitan and Rygh (1994) have highly recommended the use of light loads. These researchers also suggested that tipping should be limited in adults due to the risk of alveolar crest damage. They further claimed that interrupted light loads caused less root resorption than constant light loads, and that bodily movements caused less root resorption than tipping movements.

The claim of light interrupted loads being better than light constant loads was further reinforced by Rygh (1995) who suggested that in patients who were susceptible to root resorption, a light load on the teeth should be interrupted to allow root surface recovery. This investigator suggested that radiographic screening four months into treatment could be helpful in detecting those susceptible to root resorption. For susceptible patient, he also recommended that a Ni-Ti wire which produced a light constant load, should be allowed to become passive for a two week period following a three to four week activation period.

6.5 Clinical selection of wires

Various criteria and aids have been used to assist in the clinical selection of orthodontic wires and some of these are discussed below.

The selection of orthodontic wires have often been on the basis of 'feel' and clinical experience including the speed of tooth movement, patient comfort, lack of untoward effects, and final occlusion (Hazel, Rohan and West 1984). However, Rock and Wilson (1988) suggested that this approach was not ideal when using the new wire alloys as the 'feel' was deceptive.

Wire diameter also should not be used as the main criterion for Ni-Ti wire selection, as Ni-Ti wire behaviour varies greatly between manufacturers for the same nominal diameter (Tonner and Waters 1994). The present study supported this viewpoint.

Nomograms were introduced by Kusy (1981, 1983) for the selection of wires based on the requirement for stiffness, strength and range. This investigator used nomograms to

illustrate bending and torsional properties of round and rectangular stainless steel, Nitinol and β -Ti wires. This system used the linear part of the stress/strain curve, and did not take into account the pseudoplasticity of Ni-Ti wires. Therefore, the nomograms were not suitable for predicting the properties of superelastic Ni-Ti wires.

The so-called 'variable-modulus' concept was introduced by Burstone (1981) to aid in the selection of arch-wires. Burstone (1981) while considering that wire selection should not be based principally on the wire diameter, developed a wire stiffness number (W_S) and used the formula:

$W_S = M_S \times C_S$ —relating W_S to the material stiffness number (M_S), and the cross-sectional stiffness number (C_S). The material stiffness number of one was arbitrarily assigned to steel, which has a modulus of elasticity of 25×10^6 p.s.i.. He assigned the cross-sectional stiffness number of one to the diameter of 0.004".

An overall appliance stiffness number (S) was also introduced (Burstone 1981) and used the formula:

$S = W_S \times A_S$ —relating S to the wire stiffness (W_S) and the design stiffness factor (A_S). The design stiffness could be altered by introducing loops, changing bracket width, and varying the inter-bracket distance. Burstone (1981) suggested that the wire stiffness numbers should be displayed on wire packages to aid in the proper selection of wires. The W_S and S were useful for a wire with a linear stress/strain relationship. However, the present study showed that these parameters were not suitable for the selection of the superelastic Ni-Ti wires.

Other criteria have been used in the selection of orthodontic wires. Properties such as springback, elastic modulus, modulus of resilience, biocompatibility and environmental stability were suggested by Kapila and Sachdeva (1989) as parameters for consideration during the selection of orthodontic wires:

- a. Springback—Springback has been referred to as the maximum elastic deflection, maximum flexibility, range of activation and working range. Springback has also been related to the ratio of yield strength to elastic modulus (YS/E) by Kapila and Sachdeva (1989). However, this latter expression was awkward and is difficult to relate to superelastic Ni-Ti wires, due to their pseudoplastic behaviour.

The present study used a more appropriate term, the maximum elastic elongation (MEE) to describe this elongation during tensile loading. However, no universal agreement existed on the definition for orthodontic elastic limit (Ingram, Gipe and Smith 1986).

- b. Elastic Modulus—Differences in opinion exist for the usefulness of the elastic modulus in the selection of orthodontics wires. The elastic modulus was believed by Burstone (1981) to be the most important variable in the clinical selection of wires. However, Thurow (1982) stated “In orthodontics the modulus of elasticity is of practically no value as a criterion for selecting one material over another”. His reasoning was that “...one could completely compensate for it by an appropriate change in wire size”. This author may not have taken into account limitations on wire diameter, for example, the maximum diameter allowable for the size of the orthodontic bracket.

Irrespective of this argument, the present study showed that the elastic modulus is of far less importance than the stress required for pseudoplasticity with superelastic Ni-Ti when considering the load on the teeth.

- c. Formability—Formability was defined as the maximum permanent deformation before failure (Proffit 1993). The formability of a wire allowed it to be bent into coils and loops etc.
- d. Modulus of resilience or stored energy (M_R)—Modulus of resilience (M_R) was defined as the work available to move teeth and was indicated by the area under a stress/strain curve (Drake *et al.* 1982; Proffit 1993). The M_R could be estimated for a superelastic Ni-Ti wire by multiplying the σ_{Ms} by the PPR.
- e. Biocompatibility and environmental stability—These characteristics involve corrosion resistance and tissue tolerance.

These properties were listed and used by Kapila and Sachdeva (1989) to describe four major wire types. Their list formed a table with general recommendations and therefore was of limited use when selecting the best wire for a clinical situation. This table has been updated as shown in Table 6.4 to include information from the present and previous studies.

Table 6.4 Comparison of different wire types (Kapila and Sachdeva 1989), with updates.

Wire	S-S	Co-Cr	Ni-Ti	Beta-Ti	Multi-strand
Springback (MEE)	low (1.4%) [§]	good (2%) ^w	high (8-10%) [§] (Nitinol ~2%) [§]	average	high
Stiffness (Elastic modulus)	high (150-200 GPa) ^{§w}	high (200 GPa) ^w	low (30-40 GPa) [§]	average (71 GPa) [@]	low
σ_{Ms} [§]	--	--	~300-500 MPa [§]	--	--
ϵ_{Ms} [§]	--	--	~1-2% [§]	--	--
PPR [§]	--	--	~2.5-6% [§]	--	--
Formability	good	good	poor	good	poor
Stored energy (Resiliency)	low	low	high	average	high
Biocompatibility	good	good	--	good	good
Joinability	S/W	S/W	no	weld	S/W
Friction	low	low-mod	low-mod	high	--

-- unstated

(italics) -updates to the original table:

§ Present study (1995)

w Watanabe (1982)

@ Drake et al. (1982)

All of Ni-Ti orthodontic wires, except Nitinol, displayed distinct pseudoplastic behaviour as indicated by their stress/strain curves. However, Nitinol showed its own interesting behaviour which could not be described as purely linear, as reported by Miura *et al.* (1986). New parameters introduced in the present study are the transformation stress (σ_{Ms}), pseudoplastic range (PPR) and maximum elastic elongation (MEE). These parameters should help to define the properties of the superelastic Ni-Ti wires which are of orthodontic interest.

Chapter 7

Conclusions

The conclusions that can be drawn from this study are as follows:

1. All Ni-Ti wires tested, except Nitinol, showed distinct pseudoplastic behaviour each with a second slope on the stress/strain curves at ambient and mouth temperatures. This finding indicated that the superelastic Ni-Ti wires had undergone stress induced martensitic transformation. However, Nitinol did show some pseudoplasticity, since it showed non-linear elasticity on its unloading curve.
2. New parameters were introduced for consideration in the clinical selection of superelastic wires. These were the transformation stress (σ_{Ms}), the pseudoplastic range (PPR) and maximum elastic elongation (MEE).
3. The σ_{Ms} , measured at the pseudo-0.1% YS, was the stress required for the martensitic phase change and is related to the constant load on a tooth during the orthodontic treatment. However, the equivalent stress on the unloading plateau was more clinically applicable and was 30-50% of the loading plateau for CX Chinese Ni-Ti wire.
4. The PPR was the measurement of the length of the plateau ($\epsilon_{Mf}-\epsilon_{Mf}$), and was a useful indicator of ability of a superelastic Ni-Ti wire to impart a constant load.
5. The MEE was measured at the true 0.1% YS, as permanent deformation was thought to occur past this point.
6. The PPR and the σ_{Ms} were temperature dependent. These properties increased significantly for most of the superelastic wires when the temperature was raised from ambient to mouth temperature. This finding indicated that further thermally induced austenitic transformation occurred prior to applying stress. Although the improvement of approximately 10% for PPR for most wires is of clinical advantage, the generally small increase in σ_{Ms} may not be clinically significant.
7. The second slopes for superelastic wires were less steep than their first slopes for most wires, but improved grips and an extensometer would be

needed to precisely measure the elastic moduli. Reduced steepness of the second slope would reduce the load on a tooth if the orthodontist strained the wire beyond its PPR.

8. The Chinese Ni-Ti wires, especially the CX Enterprise Chinese Ni-Ti, showed the large variations in diameter between wires from the same batch and also on different locations of the same wire.

Traditional terminology used to describe the tensile properties of orthodontic wires was not sufficient to describe the unusual properties of the superelastic Ni-Ti wires. The new parameters that were considered clinically important include, the stress required for the start of the stress-induced martensitic transformation (σ_{Ms}) and pseudoplastic range (PPR). The maximum elastic elongation (MEE) measured at the 0.1% YS is another useful new parameter, indicating the limit of elastic elongation.

Chapter 8

Future Research

Future research recommendations are as follows:

1. Comparisons of the same wires using a three-point bending test could be carried out to determine the relationship between bending load/deflection and tensile stress/strain. If a constant relationship were proved to be present, the tensile test then could be used to predict the bending properties.
2. Comparisons of the unloading curves of the same wires tested in the present study could be carried out. The new generation of Ni-Ti wires, eg., copper Ni-Ti, could also be included.
3. A precise determination of the temperature transition range (TTR) of the test wires could be obtained using the differential thermal analysis (DTA).
3. More accurate measurements of the elastic moduli could be achieved with the development of small wrap-around grips and the use of an extensometer.
4. The effect of long term distortion for up to three months on mechanical properties and permanent deformation of superelastic Ni-Ti wires. This research should be designed to simulate the use of the wire during orthodontic treatment.
5. Fatigue testing of wires and its interrelationship to factors such as surface composition and impurities could be investigated.
6. Testing Nitinol and Nitinol SE could be carried out at higher temperatures to assess Nitinol for a possible austenitic phase change and to assess Nitinol SE for an improved austenitic phase change. Nitinol and Nitinol SE may improve their pseudoplasticity at a high temperature.
7. Measuring the oral temperature range in which the superelastic Ni-Ti wires work could be important, in order to assess whether these wires were operating in their optimal temperature range. Some mouth-breathers or inhabitants of cold countries could have temperatures in the anterior part of the mouth too low for some superelastic Ni-Ti wires. Should the oral temperature be lower than the TTR of a superelastic Ni-Ti wire, the thermally induced phase change to austenite when placed in the mouth would be hindered.

Appendix 1

Tensile Test Data at Ambient Temperature

Wilcock Premium Plus Stainless Steel
 Tensile tested at ambient temperature
 Test date: 20 Apr 94 Batch: KH.RKK

Spec. No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S (MPa)	Elongation at Fracture (%)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.404	51.0	21.0	162.6	1758.26	2657.0	2.27	1.26
2	0.401	50.9	21.0	139.4	1897.72	2406.3	2.00	1.48
3	0.401	50.5	21.0	162.6	1921.32	2665.9	2.92	1.47
4	0.401	50.1	21.0	148.5	1675.83	2670.6	2.53	1.31
5	0.401	50.0	21.0	147.2	1633.27	2566.7	2.82	1.25
Mean				152.1	1777.28	2593.3	2.51	1.35
S.D.				10.2	129.08	112.9	0.38	0.11

Nitinol Activ-arch NiTi

Tensile tested at ambient temperature

Test date: 25 May 94 Batch: 053

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.402	50	24.5	38.41	596.09	1563.08	6.73	1.93
2	0.403	50	24.5	39.56	564.09	1608.15	7.18	1.74
3	0.401	50	24.5	39.67	571.35	1577.84	7.00	1.80
4	0.401	50	24.5	40.19	570.16	1657.98	7.69	1.80
5	0.403	50	25	38.71	543.71	1615.05	8.22	1.90
6	0.402	50	25	39.51	553.15	1685.21	8.43	1.70
Mean				39.34	566.43	1617.89	7.54	1.81
S.D.				0.66	17.98	46.58	0.69	0.09

CX Enterprises Chinese NiTi

Tensile tested at ambient temperature

Test date: 27 Apr 94 Batch: None indicated

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2 nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.392	50.0	24.0	38.2	1304.69	1514.9	9.59	345.95	48.00	1.07	6.47	5.40	8.59
2	0.407	50.0	24.0	39.1	1416.33	1499.2	9.42	328.85	42.16	0.96	6.20	5.24	8.82
3	0.408	50.0	24.0	40.1	1565.26	1568.5	9.92	326.70	35.89	0.91	6.38	5.47	9.88
4	0.405	50.0	24.0	40.8	1438.82	1441.1	8.88	337.29	42.45	1.00	6.20	5.20	8.87
5	0.410	50.0	24.5	40.7	1336.92	1503.8	10.77	295.41	32.38	0.84	6.33	5.49	9.55
6	0.403	50.0	24.5	41.6	1290.47	1481.3	9.47	339.47	42.45	0.95	6.13	5.18	8.44
Mean				40.1	1392.08	1501.5	9.67	328.94	40.56	0.96	6.29	5.33	9.03
S.D.				1.2	103.70	41.8	0.63	17.88	5.55	0.08	0.13	0.14	0.57

ORSU 'Genuine' Chinese NiTi

Tensile tested at ambient temperature

Test date: 25 May 94 Batch: Nil indicated

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2 nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.411	50	24	50.71	1363.64	1453.87	9.41	460.12	32.63	1.13	6.21	5.08	8.93
2	0.410	50	24	44.95	1253.21	1408.12	9.41	486.29	32.54	1.33	6.27	4.94	8.59
3	0.410	50	24.5	47.46	1207.39	1387.67	9.22	499.92	39.89	1.33	6.27	4.94	8.10
4	0.412	50	24.5	44.34	1336.73	1349.86	9.02	497.34	39.00	1.53	6.40	4.87	8.67
5	0.412	50	24.5	45.89	1294.73	1369.36	8.99	501.09	38.71	1.53	6.40	4.87	8.53
Mean				46.67	1294.14	1393.78	9.21	488.95	36.56	1.37	6.31	4.94	8.56
S.D.				2.55	62.85	39.93	0.20	17.15	3.65	0.17	0.09	0.09	0.30

Sentalloy Medium NiTi

Tensile tested at ambient temperature

Test date: 11 May 94 Batch: D1013

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{Mf} (%) (at plateau end)	PPR (%) ($\epsilon_{Mf} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.407	50	22.5	27.6	963.2	1266.8	13.3	290.6	18.7	1.25	5.42	4.17	9.2
2	0.407	50	22.5	29.9	928.2	1273.0	13.9	293.3	18.0	1.19	5.31	4.12	8.9
3	0.407	50	23.0	23.2	996.6	1201.9	12.3	299.4	18.0	1.55	5.63	4.08	9.9
4	0.408	50	23.0	27.4	978.4	1249.5	13.1	301.0	21.4	1.38	5.33	3.95	8.8
5	0.407	50	23.0	27.4	811.0	1261.8	13.1	293.3	21.5	1.28	5.30	4.02	8.0
6	0.407	50	23.0	27.2	975.9	1232.6	12.7	299.0	21.6	1.38	5.57	4.19	8.8
Mean				27.1	942.2	1247.6	13.1	296.1	19.9	1.34	5.43	4.09	8.9
S.D.				2.2	68.2	26.6	0.5	4.3	1.8	0.13	0.14	4.09	0.7

Dentaurum Rematitan 'Lite' Ni-Ti
Tensile tested at ambient temperature
Test date: 25 May 94 Batch: 71744

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.409	50	25	30.30	996.04	1282.64	12.03	433.50	22.13	1.78	6.88	5.10	9.43
2	0.409	50	25	30.21	1031.44	1281.88	11.89	431.61	22.51	1.73	6.83	5.10	9.53
3	0.409	50	25	31.06	993.38	1276.17	11.86	435.03	22.27	1.73	6.74	5.01	9.37
4	0.409	50	25	30.05	997.20	1266.10	11.84	436.30	22.11	1.77	6.83	5.06	9.40
5	0.409	50	25	30.40	1034.69	1267.61	12.26	429.48	18.24	1.73	6.80	5.07	10.00
6	0.409	50	25	28.35	1090.38	1281.85	12.37	431.93	23.49	1.94	7.04	5.10	9.97
Mean				30.06	1023.86	1276.04	12.04	432.98	21.79	1.78	6.85	5.07	9.62
S.D.				0.91	37.45	7.50	0.22	2.48	1.81	0.08	0.10	0.04	0.29

Ormco NiTi

Tensile tested at ambient temperature
 Test date: 18 May 94 Batch: 3K133K

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.408	50	23.0	33.5	1068.6	1347.8	12.1	362.2	21.9	1.47	5.15	3.68	8.6
2	0.408	50	23.5	35.8	1063.6	1348.6	12.8	359.5	20.6	1.40	5.31	3.91	8.8
3	0.407	50	23.5	34.0	1024.7	1328.3	12.4	371.7	21.3	1.77	5.49	3.72	8.7
4	0.408	50	23.5	35.6	1016.2	1322.2	11.8	363.1	20.6	1.33	5.12	3.79	8.3
5	0.408	50	23.5	33.4	1062.0	1353.3	12.9	379.7	19.8	1.43	5.15	3.72	8.9
6	0.407	50	23.5	35.0	892.3	1333.3	12.3	364.9	21.4	1.46	5.23	3.77	7.7
7	0.407	50	23.5	33.0	1056.6	1325.2	12.3	364.7	19.8	1.40	5.33	3.93	9.0
Mean				34.3	1026.3	1337.0	12.4	366.6	20.8	1.47	5.25	3.75	8.6
S.D.				1.1	62.5	12.7	0.4	6.9	0.8	0.14	0.13	0.10	0.4

TP Reflex Ni-Ti

Tensile tested at ambient temperature

Test date: 18 May 94 Batch: 382-116

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.412	50	24	53.4	1082.8	1241.5	11.9	320.7	19.4	0.83	6.72	5.99	10.1
2	0.413	50	24	43.8	995.4	1259.3	13.7	305.7	19.4	0.83	6.81	5.98	10.1
3	0.413	50	24	47.8	991.7	1281.4	13.3	294.1	19.7	0.69	6.78	6.09	10.0
4	0.413	50	24	40.0	1006.6	1276.5	13.1	291.9	19.2	0.96	7.01	6.05	10.2
5	0.414	50	24	41.3	1011.2	1288.4	13.7	300.8	17.2	0.83	6.93	6.10	10.4
6	0.414	50	24	43.5	995.5	1227.2	12.5	292.7	19.2	0.77	6.93	6.16	10.1
Mean				45.0	1013.9	1262.4	13.0	301.0	19.0	0.80	6.86	6.06	10.1
S.D.				4.9	34.6	24.2	0.7	11.0	0.9	0.10	0.11	0.07	0.2

3M Unitek Superelastic Nickel Titanium

Tensile tested at ambient temperature

Test date: 25 May 94 Batch: 502

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.398	50	25	29.49	1162.78	1428.46	10.55	429.29	21.39	1.73	4.35	2.62	8.20
2	0.397	50	25	29.98	1070.45	1414.20	10.76	433.43	20.99	1.77	4.35	2.58	7.83
3	0.397	50	25	29.62	1256.26	1428.34	10.36	431.00	21.38	1.71	4.21	2.50	8.61
4	0.397	50	25	29.72	1180.32	1425.92	10.57	434.64	21.35	1.81	4.38	2.57	8.34
5	0.397	50	25	29.70	1229.60	1417.84	10.20	434.24	21.69	1.70	4.35	2.65	8.41
6	0.397	50	25	29.86	1221.12	1413.80	10.52	433.83	21.64	1.90	4.32	2.42	8.56
Mean				29.73	1186.76	1421.43	10.49	432.74	21.41	1.77	4.33	2.56	8.33
S.D.				0.17	66.32	6.94	0.19	2.12	0.25	0.08	0.06	0.08	0.28

Appendix 2

Tensile Test Data at Mouth Temperature

Nitinol Activ-arch

Tensile tested at mouth temperature

Test date: 2 Nov 94 Batch: 304

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.398	50.0	37.1	38.15	574.36	1755.39	10.17	1.60
2	0.399	50.0	37.1	37.51	631.05	1777.57	9.84	1.80
3	0.398	50.0	37.1	35.23	711.82	1756.43	9.24	2.13
4	0.398	50.0	36.9	34.94	667.60	1724.28	9.17	2.03
5	0.400	50.0	37.0	37.25	674.44	1749.72	9.18	1.91
Mean				36.62	651.85	1752.68	9.52	1.89
S.D.				1.44	51.94	19.18	0.46	0.21

CX Enterprises Chinese NiTi

Tensile tested at mouth temperature

Test date: 28 Nov 94 Batch: Nil indicated

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{Mf} (%) (at plateau end)	PPR (%) ($\epsilon_{Mf} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.405	50.0	36.9	35.01	1118.62	1436.50	10.29	410.26	37.51	1.33	6.67	5.34	8.60
2	0.405	50.0	36.9	33.34	1242.04	1420.97	9.56	403.66	39.24	1.30	6.56	5.26	8.67
3	0.405	50.0	36.9	36.25	1094.16	1414.76	9.78	413.76	38.09	1.27	6.61	5.34	8.40
4	0.405	50.0	36.9	37.60	1147.73	1402.73	9.67	405.60	39.35	1.23	6.56	5.33	8.46
5	0.407	50.0	37.0	33.56	1232.60	1379.43	9.64	405.49	38.42	1.33	6.61	5.28	8.80
Mean				35.15	1167.03	1410.88	9.79	407.75	38.52	1.29	6.60	5.31	8.59
S.D.				1.81	66.99	21.38	0.29	4.15	0.78	0.04	0.05	0.04	0.16

ORSU 'Genuine' Chinese NiTi

Tensile tested at mouth temperature

Test date: 19 Oct 94 Batch: Ni 040

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{Mf} (%) (at plateau end)	PPR (%) ($\epsilon_{Mf} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.402	50.0	36.9	40.43	1413.21	1466.78	9.24	464.50	33.51	1.33	6.00	4.67	8.87
2	0.402	50.0	36.8	45.86	1224.49	1290.28	10.11	473.17	33.46	1.37	7.20	5.83	9.26
3	0.400	50.0	36.6	44.14	1200.86	1278.05	9.29	481.86	35.39	1.27	6.96	5.69	8.80
4	0.400	50.0	37.0	44.30	1154.70	1243.04	9.55	479.07	34.18	1.23	6.88	5.65	8.67
5	0.400	50.0	37.0	45.92	1200.40	1246.40	9.11	470.80	33.46	1.20	6.78	5.58	8.77

Mean

44.13 1238.73 1304.91 9.46 473.88 34.00 1.28 6.76 5.48 8.87

S.D.

2.23 100.76 92.72 0.40 6.87 0.83 0.07 0.45 0.46 0.23

Sentalloy Medium NiTi

Tensile tested at mouth temperature

Test date: 19 Oct 94 Batch: D1013

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{Mf} (%) (at plateau end)	PPR (%) ($\epsilon_{Mf} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.406	50.0	37.8	31.73	984.94	1271.92	12.97	342.21	22.02	1.27	6.03	4.76	8.94
2	0.406	50.0	37.1	30.24	992.28	1246.43	12.08	320.59	22.49	1.16	5.92	4.76	8.77
3	0.406	50.0	36.8	31.02	859.41	1264.58	12.43	323.29	21.90	1.10	6.00	4.90	8.13
4	0.406	50.0	36.9	32.30	987.64	1264.58	12.73	330.24	21.94	1.10	5.92	4.82	8.77
5	0.406	50.0	37.1	32.29	982.23	1277.33	12.74	324.45	22.04	1.13	5.92	4.79	8.73
Mean				31.52	961.30	1264.97	12.59	328.16	22.08	1.15	5.96	4.81	8.67
S.D.				0.89	57.08	11.67	0.34	8.91	0.24	0.07	0.05	0.06	0.31

Dentaurum Rematitan 'Lite' Ni-Ti
Tensile tested at mouth temperature
Test date: 2 Nov 94 Batch: 71744

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.410	50.0	37.1	41.24	1046.81	1331.62	11.89	445.77	21.92	1.2	6.83	5.63	9.36
2	0.410	50.0	36.9	40.74	1010.45	1331.62	12.11	432.51	22.08	1.14	6.88	5.74	9.27
3	0.410	50.0	37.1	39.90	918.42	1319.12	11.99	442.36	22.05	1.31	6.98	5.67	8.94
4	0.410	50.0	37.1	42.13	1011.97	1323.28	12.39	431.75	19.43	1.10	6.88	5.78	9.53
5	0.410	50.0	37.0	40.19	1061.58	1307.76	12.61	442.36	18.70	1.47	7.26	5.79	10.26
Mean				40.84	1009.85	1322.68	12.20	438.95	20.84	1.24	6.97	5.72	9.47
S.D.				0.89	55.69	9.94	0.30	6.39	1.64	0.15	0.17	0.07	0.49

Ormco NiTi

Tensile tested at mouth temperature

Test date: 28 Oct 94 Batch: 3K133K

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.408	50.0	37.1	32.82	1080.47	1337.12	12.05	398.15	22.20	1.30	5.58	4.28	8.54
2	0.408	50.0	37.1	32.63	1072.82	1314.54	11.35	405.80	22.02	1.33	5.60	4.27	8.50
3	0.406	50.0	37.2	30.90	1082.66	1333.33	11.73	414.45	22.04	1.43	5.60	4.17	8.60
4	0.407	50.0	37.3	30.35	993.54	1310.25	11.71	411.25	20.58	1.43	5.52	4.09	8.23
5	0.407	50.0	37.0	30.47	1076.18	1341.76	12.11	412.02	21.84	1.37	5.44	4.07	8.47
Mean				31.43	1061.13	1327.40	11.79	408.33	21.74	1.37	5.55	4.18	8.47
S.D.				1.20	37.98	14.10	0.31	6.51	0.66	0.06	0.07	0.16	0.14

TP Reflex Ni-Ti

Tensile tested at mouth temperature

Test date: 19 Oct 94 Batch: 382-116

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.411	50.0	37.1	44.95	955.07	1229.08	11.85	415.35	23.38	1.23	7.28	6.05	9.27
2	0.413	50.0	37.2	44.64	1003.66	1245.52	12.24	430.73	22.36	1.10	7.04	5.94	9.40
3	0.413	50.0	37.0	41.96	954.02	1254.11	12.58	431.47	21.36	1.17	7.04	5.87	9.30
4	0.413	50.0	37.1	42.90	1059.64	1262.32	12.23	432.22	23.05	1.17	7.09	5.92	9.66
5	0.414	50.0	36.9	40.30	1038.93	1231.33	11.86	413.42	23.28	1.30	7.29	5.95	9.70
Mean				42.95	1002.26	1244.47	12.15	424.64	22.69	1.19	7.15	5.95	9.47
S.D.				1.93	47.94	14.34	0.31	9.40	0.84	0.08	0.13	0.07	0.20

3M Unitek Superelastic Nickel Titanium
Tensile tested at mouth temperature
Test date: 19 Oct 94 Batch: 502

Spec No.	Ave. Diam (mm)	Test Length (mm)	Test Temp (°C)	1st slope Elastic Modulus (GPa)	0.1% Yield Strength (MPa)	U.T.S. (MPa)	Elongation at Fracture (%)	σ_{Ms} (pseudo 0.1% YS) (MPa)	2nd slope Elastic Modulus (GPa)	ϵ_{Ms} (%) (at pseudo 0.1% YS)	ϵ_{MF} (%) (at plateau end)	PPR (%) ($\epsilon_{MF} - \epsilon_{Ms}$)	Max. Elastic Elong. (%) (at 0.1% YS)
1	0.404	50.0	37.0	29.75	1255.66	1492.98	10.77	448.20	20.24	1.63	4.24	2.61	8.57
2	0.403	50.0	36.9	29.41	1232.46	1475.89	10.78	461.39	20.18	1.70	4.27	2.57	8.50
3	0.403	50.0	37.1	31.69	1245.39	1450.01	10.97	462.17	20.57	1.67	4.51	2.84	8.60
4	0.401	50.0	36.8	32.03	1221.49	1495.49	11.48	466.82	20.48	1.67	4.48	2.81	8.47
5	0.401	50.0	37.0	32.07	1035.00	1467.37	11.34	467.61	19.40	1.70	4.48	2.78	7.70
Mean				30.99	1198.00	1476.35	11.07	461.24	20.17	1.67	4.40	2.72	8.37
S.D.				1.30	92.03	18.83	0.33	7.79	0.46	0.03	0.13	0.12	0.38

Appendix 3

Statistical Analyses

The data were analysed using an analysis of variance (F-Test) as a 2 x 7 factorial design on the MINITAB statistical package. The Tukey's HSD (*honestly significant difference*) test with a critical value of $P = 0.05$ from the SAS/STATS statistical package was used to rank the means for the tensile parameters. A harmonic mean of repetitions was used.

The paired t-test was used to compare the first slope elastic modulus with that of the second slope for each superelastic wire, at both ambient and mouth temperatures. Significance was at $P < 0.05$.

<u>Index for analyses</u>	Page
First Slope Elastic Modulus	61
0.1% Yield Strength	61
Ultimate Tensile Strength (UTS)	62
Elongation at Fracture	62
'Pseudo'-0.1% Yield Strength (σ_{Ms})	63
Second Slope Elastic Modulus	63
Differences between First and Second Elastic Moduli	64
Elongation at M_s (ϵ_{Ms})	65
Elongation at M_f (ϵ_{Mf})	65
Pseudoplastic Range (PPR)	66
Maximum Elastic Elongation (MEE), at 0.1% Yield Strength	66

Analysis of Variance for First Slope Elastic Modulus

Source	DF	Seq SS	EMS	F-value	P
Temp	1	3.91	0.60	0.16	0.688
Type	7	2649.06	367.94	99.26	0.000
Temp*Type	7	511.59	73.08	19.72	0.000
Error	72	266.89	3.71		
Total	87	3431.45			

Means for Elastic Modulus (GPa)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures					
	Ambient		Mouth			Ambient		Mouth	
NT	39.34	b	36.62	b	NT	39.34	a	36.62	a
CX	40.08	b	35.15	bc	CX	40.08		35.15	
OR	46.67	a	44.13	a	OR	46.67	a	44.13	a
SA	27.12	d	31.52	c	SA	27.12		31.52	
RL	30.06	d	40.84	a	RL	30.06		40.84	
OM	34.33	c	31.43	c	OM	34.33	a	31.43	a
TP	44.97	a	42.95	a	TP	44.97	a	42.95	a
SE	29.73	d	30.99	c	SE	29.73	a	30.99	a

a : denotes no significant difference between temperatures

Analysis of Variance for Log 0.1% Yield Strength

A natural log transformation was performed because of the heterogeneity of variance for this parameter.

Source	DF	Seq SS	EMS	F-value	P
Temp	1	0.00000	0.00058	0.16	0.688
Type	7	4.39650	0.60772	170.79	0.000
Temp*Type	7	0.14597	0.02085	5.86	0.000
Error	72	0.25620	0.00356		
Total	87	4.79867			

Means for Log 0.1% yield strength (MPa)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures					
	Ambient		Mouth			Ambient		Mouth	
NT	6.339	d	6.477	c	NT	6.339		6.477	
CX	7.236	a	7.061	ab	CX	7.236		7.061	
OR	7.162	ab	7.119	a	OR	7.162	a	7.119	a
SA	6.846	c	6.867	b	SA	6.846	a	6.867	a
RL	6.931	c	6.916	b	RL	6.931	a	6.916	a
OM	6.932	c	6.967	b	OM	6.932	a	6.967	a
TP	6.919	c	6.909	b	TP	6.919	a	6.909	a
SE	7.078	b	7.086	ab	SE	7.078	a	7.086	a

a : denotes no significant difference between temperatures

Analysis of Variance for Ultimate Tensile Strength (UTS)

Source	DF	Seq SS	EMS	F-value	P
Temp	1	878	548	0.49	0.486
Type	7	1555705	225149	201.58	0.000
Temp*Type	7	110082	15726	14.08	0.000
Error	72	80418	1117		
Total	87	1747082			

Means for Ultimate Tensile Strength (MPa)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures					
	Ambient		Mouth			Ambient		Mouth	
NT	1618	a	1753	a	NT	1618		1753	
CX	1501	b	1411	b	CX	1501		1411	
OR	1394	cd	1305	cd	OR	1394		1305	
SA	1248	f	1265	cd	SA	1248	a	1265	a
RL	1276	ef	1323	c	RL	1276	a	1323	a
OM	1337	de	1327	c	OM	1337	a	1327	a
TP	1262	f	1244	d	TP	1262	a	1244	a
SE	1421	c	1476	b	SE	1421	a	1476	a

a : denotes no significant difference between temperatures

Analysis of Variance for Elongation at Fracture

Source	DF	Seq SS	EMS	F-value	P
Temp	1	0.538	1.080	5.87	0.018
Type	7	225.930	30.555	166.04	0.000
Temp * Type	7	16.097	2.300	12.50	0.000
Error	72	13.250	0.184		
Total	87	255.815			

Means for Elongation at Fracture (%)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures					
	Ambient		Mouth			Ambient		Mouth	
NT	7.542	e	9.520	c	NT	7.542		9.520	
CX	9.025	d	9.788	c	CX	9.025	a	9.788	a
OR	9.210	d	9.460	c	OR	9.210	a	9.460	a
SA	13.067	a	12.590	a	SA	13.067	a	12.590	a
RL	12.042	b	12.198	a	RL	12.042	a	12.198	a
OM	12.371	ab	11.790	ab	OM	12.371	a	11.790	a
TP	13.033	a	12.152	a	TP	13.033	a	12.152	a
SE	10.493	c	11.068	b	SE	10.493	a	11.068	a

a : denotes no significant difference between temperatures

Analysis of Variance for Log 'Pseudo'-0.1% Yield Strength (σ_{1s})

A natural log transformation was performed because of the heterogeneity of variance for this parameter.

Source	DF	Seq SS	EMS	F-value	P
Temp	6	1.55786	0.24740	413.12	0.000
Type	1	0.25861	0.25082	418.83	0.000
Temp*Type	6	0.26174	0.04362	72.85	0.000
Error	63	0.03773	0.00060		
Total	76	2.11594			

Means for Log 'Pseudo'-0.1% yield strength

Tukey's HSD Rankings

Within Temperatures				Between Temperatures					
	Ambient		Mouth			Ambient		Mouth	
CX	5.795	d	6.011	d	CX	5.795		6.011	
OR	6.192	a	6.161	a	OR	6.192	a	6.161	a
SA	5.691	e	5.780	e	SA	5.691		5.780	
RL	6.071	b	6.084	bc	RL	6.071	a	6.084	a
OM	5.904	c	6.012	d	OM	5.904		6.012	
TP	5.707	e	6.051	cd	TP	5.707		6.051	
SE	6.070	b	6.134	ab	SE	6.070		6.134	

a : denotes no significant difference between temperatures

Analysis of Variance for Second Slope Elastic Modulus

Source	DF	Seq SS	EMS	F-value	P
Temp	1	2.84	0.00	0.00	0.983
Type	6	4291.95	701.42	163.79	0.000
Temp*Type	6	86.94	14.49	3.38	0.006
Error	63	269.79	4.28		
Total	76	4651.51			

Means for second slope elastic modulus (GPa)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures					
	Ambient		Mouth			Ambient		Mouth	
CX	40.56	a	38.52	a	CX	40.56	a	38.52	a
OR	36.55	a	34.00	b	OR	36.55	a	34.00	a
SA	19.87	b	22.08	c	SA	19.87	a	22.08	a
RL	21.79	b	20.84	c	RL	21.79	a	20.84	a
OM	20.77	b	21.74	c	OM	20.77	a	21.74	a
TP	19.02	b	22.69	c	TP	19.02	a	22.69	a
SE	21.41	b	20.17	c	SE	21.41	a	20.17	a

a : denotes no significant difference between temperatures

T-Test to test if the Means of First and Second Elastic Moduli are Different at Ambient Temperature

Test of $\mu = 0.000$ vs $\mu \text{ not } = 0.000$

Type	N	Mean	StDev	SE Mean	T	P-Value
CX	6	-0.47	6.24	2.55	-0.19	<u>0.86</u>
OR	5	10.12	5.16	2.31	4.38	0.012
SA	6	7.25	2.63	1.07	6.75	0.0011
RL	6	8.27	2.34	0.96	8.64	0.0003
OM	7	13.56	1.26	0.48	28.54	0.0000
TP	6	25.95	4.57	1.87	123.90	0.0000
SE	6	8.32	0.35	0.14	58.25	0.0000

T-Test to test if the Means of First and Second Elastic Moduli are Different at Mouth Temperature

Test of $\mu = 0.000$ vs $\mu \text{ not } = 0.000$

Type	N	Mean	StDev	SE Mean	T	P-Value
CX	5	-3.370	1.894	0.847	-3.98	0.016
OR	5	10.130	2.387	1.067	9.49	0.0007
SA	5	9.438	1.065	0.476	19.82	0.0000
RL	5	20.004	2.024	0.905	22.10	0.0000
OM	5	9.698	0.939	0.420	23.08	0.0000
TP	5	20.264	2.036	0.910	22.26	0.0000
SE	5	10.816	1.440	0.644	16.80	0.0001

Analysis of Variance for the Differences between the First and Second Elastic Moduli

Source	DF	Seq SS	EMS	F-Value	P
Temp	1	4.54	6.17	0.69	0.410
Type	6	3679.24	605.60	67.62	0.000
Temp*Type	6	554.66	92.44	10.32	0.000
Error	63	564.23	8.96		
Total	76	4802.67			

Means for the Difference between the First and Second Elastic Moduli (GPa)

Tukey's HSD Rankings

	Within Temperatures				Between Temperatures			
	Ambient		Mouth		Ambient		Mouth	
CX	0.472	d	3.370	c	0.472	a	3.370	a
OR	-10.116	bc	-10.130	b	-10.116	a	-10.130	a
SA	-7.250	c	-9.438	b	-7.250	a	-9.438	a
RL	-8.270	bc	-20.004	a	-8.270		-20.004	
OM	-13.557	b	-9.698	b	-13.557	a	-9.698	a
TP	-25.950	a	-20.264	a	-25.950	a	-20.264	a
SE	-8.322	bc	-10.816	b	-8.322	a	-10.816	a

a : denotes no significant difference between temperatures

Analysis of Variance for Elongation at Ms (ϵ_{Ms})

Source	DF	Seq SS	EMS	F-value	P
Temp	1	0.02882	0.02887	2.90	0.094
Type	6	4.25702	0.64580	64.86	0.000
Temp*Type	6	1.64993	0.27499	27.62	0.000
Error	63	0.62729	0.00996		
Total	76	6.56307			

Means for Elongation at Ms (%)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures					
	Ambient		Mouth			Ambient		Mouth	
CX	0.9550	c	1.2920	b	CX	0.9550		1.2920	
OR	1.3700	b	1.2800	b	OR	1.3700	a	1.2800	a
SA	1.3383	b	1.1520	b	SA	1.3383		1.1520	
RL	1.7800	a	1.2440	b	RL	1.7800		1.2440	
OM	1.4657	b	1.3720	b	OM	1.4657	a	1.3720	a
TP	0.8017	c	1.1940	b	TP	0.8017		1.1940	
SE	1.7700	a	1.6740	a	SE	1.7700	a	1.6740	a

a : denotes no significant difference between temperatures

Analysis of Variance for Elongation at Mf (ϵ_{Mf})

Source	DF	Seq SS	EMS	F-value	P
Temp	1	1.9526	1.6516	66.45	0.000
Type	6	59.9145	9.9151	398.90	0.000
Temp*Type	6	0.4466	0.0744	2.99	0.012
Error	63	1.5659	0.0249		
Total	76	63.8796			

Means for Elongation at Mf (%)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures					
	Ambient		Mouth			Ambient		Mouth	
CX	6.285	b	6.602	b	CX	6.285	a	6.602	a
OR	6.310	b	6.764	b	OR	6.310		6.764	
SA	5.427	c	5.958	c	SA	5.427		5.958	
RL	6.853	a	6.966	a	RL	6.853	a	6.966	a
OM	5.254	c	5.548	d	OM	5.254	a	5.548	a
TP	6.863	a	7.148	a	TP	6.863	a	7.148	a
SE	4.327	d	4.396	e	SE	4.327	a	4.396	a

a : denotes no significant difference between temperatures

Analysis of Variance for Pseudoplastic Range (PPR)

Source	DF	Seq SS	EMS	F-value	P
Temp	1	2.5004	2.1281	103.19	0.000
Type	6	84.6866	13.9081	674.40	0.000
Temp*Type	6	1.7831	0.2972	14.41	0.000
Error	63	1.2992	0.0206		
Total	76	90.2693			

Means for Pseudoplastic range (%)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures			
Ambient		Mouth		Ambient		Mouth	
CX	5.330 b	5.310 c		CX	5.330 a	5.310 a	
OR	4.940 c	5.484 bc		OR	4.940	5.484	
SA	4.088 d	4.806 d		SA	4.088	4.806	
RL	5.073 c	5.722 ab		RL	5.073	5.722	
OM	3.789 e	4.196 e		OM	3.789	4.196	
TP	6.062 a	5.940 a		TP	6.062 a	5.940 a	
SE	2.557 f	2.722 f		SE	2.557	2.722	

a : denotes no significant difference between temperatures

Analysis of Variance for Maximum Elastic Elongation (MEE), at 0.1% Yield Strength

Source	DF	Seq SS	EMS	F-value	P
Temp	1	1.170	1.164	9.24	0.003
Type	7	511.390	71.973	570.89	0.000
Temp*Type	7	3.842	0.549	4.35	0.000
Error	72	9.077	0.126		
Total	87	525.478			

Means for Elongation at 0.1% Yield Strength (%)

Tukey's HSD Rankings

Within Temperatures				Between Temperatures			
Ambient		Mouth		Ambient		Mouth	
NT	1.812 d	1.894 c		NT	1.812 a	1.894 a	
CX	9.675 a	8.586 b		CX	9.675	8.586	
OR	8.564 c	8.874 ab		OR	8.564 a	8.874 a	
SA	8.933 bc	8.668 b		SA	8.933 a	8.668 a	
RL	9.617 ab	9.472 a		RL	9.617 a	9.472 a	
OM	8.571 c	8.468 b		OM	8.571 a	8.468 a	
TP	10.150 a	9.466 a		TP	10.150 a	9.466 a	
SE	8.325 c	8.368 b		SE	8.325 a	8.368 a	

a : denotes no significant difference between temperatures

Appendix 4

1994 IADR Meeting, Australia and New Zealand Division: Abstract No. 81

Comparison of Tensile Properties of Nickel Titanium Wires.
G. STANTON*, T. MORI and M. SIMS (Faculty of Dentistry,
University of Sydney, Australia).

Wires of various compositions are used in orthodontic treatment. The purpose of this study was to compare nickel-titanium wires by assessing their tensile properties. Eight commercial wires, 0.4 mm in diameter, were tested at a cross-head speed of 1 mm/min under ambient and mouth temperatures. A stainless steel wire was included for comparison. At least five specimens were tested for each wire. After the initial linear relationship between load and elongation (modulus of elasticity), the nickel-titanium wires showed characteristic pseudoplastic behaviour (often called superelasticity) and then a second linear relationship in all but one (Nitinol). A new parameter has been defined as the 'superelastic working range' (SER) and measured as a percentage of the initial gauge length. SER ranged from 2-6%. The values for modulus of elasticity ranged from 27-42 GPa for the first slope. The values were significantly reduced in the second slope in most superelastic wires. Other properties obtained with the superelastic nickel-titanium wires were 300-490 MPa for 'pseudo'-0.1% yield strength, 8-10% elastic elongation, and 1250-1500 MPa for ultimate tensile strength. Significant differences in the superelastic working range (SER) exist amongst the superelastic nickel-titanium wires.

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