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Differences in the pseudoelasticity behaviour of nickel–titanium orthodontic wires

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The variations in superelasticity behaviour have been studied for three orthodontics wires. Chemical compositions, microstructures, transformation temperatures and induced martensitic transformation stresses have been determined in each alloy. Tension tests were carried out at room temperature (20 °C) and body temperature with physiological environment at 37 °C in order to determine the small force which the orthodontist can apply for bone remodelling processes.

1. Introduction

The shape memory effect and the pseudoelasticity of NiTi alloys were developed by Buehler *et al.* [1] in the early 1960s and introduced into orthodontic applications by Andreasen *et al.* [2–5]. These properties are related to a thermoelastic martensitic transformation (austenite → martensite) which can be produced by cooling or may be stress induced.

Martensite formation can be initiated by cooling the material below M_s, defined as the temperature at which the martensitic transformation begins. M_f is the temperature at which martensitic transformation finishes. The transformation is reversible, with A_s the temperature at which the reverse austenitic transformation (martensite → austenite) begins upon heating, and A_f the temperature at the end of the reverse austenitic transformation.

The property 'shape memory' is the characteristic of being able to return to a previously manufactured shape when heated above A_f. To use this property, a wire must first be set into the desired shape and held while undergoing a high-temperature heat treatment. After the wire has cooled to room temperature it may be deformed within certain strain limits. When heated to its unique A_f, it will remember its shape and return to the original configuration.

With respect to thermoelastic martensitic transformations there are similar roles for temperature and stress. Thus, when stress is applied to a specimen in the austenitic state, martensite plates form and grow continuously with rising stress, and disappear as the stress is lowered.

The stress–strain curve in the austenitic state shows that after linear elastic deformation of the austenitic phase, there follows a non-linear elastic behaviour based on the stress-induced martensite. These alloys, strained to about 10–15%, revert to their original shape when a sample is unloaded. This behaviour is called pseudoelasticity and allows the orthodontist to apply an almost continuous light force with larger activations that result in a reduction of tissue trauma and patient discomfort, this facilitating enhanced tooth movement [6, 7].

Tooth movement during orthodontic therapy is achieved by applying forces to teeth which result in bone remodelling processes. The elastic deformation of an orthodontic wire and the subsequent release of its elastic energy over a period of time gives rise to the correcting forces. It is generally assumed that optimal tooth movement is achieved by applying forces that are low in magnitude and continuous in nature. Such forces minimize tissue destruction and produce a relatively constant stress in the periodontal ligament during tooth movement.

2. Experimental procedure

Three orthodontic wires with different pseudoelastic recovery at room temperature have been studied. Chemical compositions have been determined by gravimetric analysis with a maximum error 0.1% in all cases. Table I gives the overall composition of the alloys.

The samples were ground with fine grain abrasive paper and running water and polished with a 0.05 μm alumina solution. This was done in order to avoid a change in the original structure due to the effects of grinding and polishing, since small amounts of thermal and mechanical energy can influence martensitic transformation. Chemical etching was carried out with an acid mixture.

A scanning electron microscope was used for metallographic observation, the acceleration potential being 25 kV.

TABLE I Chemical composition (% weight)

Alloy	Ni (%)	Ti (%)
A	64.6	36.4
B	62.4	37.6
C	63.0	37.0

The samples were heated to 900 °C for 10 min followed by water quenching at 20 °C. The transformation temperatures were determined 24 h after this heat treatment. The flow calorimeter used here measures differential signals (ΔT) by means of thermobatteries which consist of 32 p–n juntion thermocouples connected in opposition. Temperature was measured by means of a standard Pt-100 probe. All signals were digitalized through a multichannel recorder linked to a microcomputer. The sensitivity of this calorimeter technique is approximately 100 times higher than other conventional methods such as differential thermal analysis (DTA) or differential scanning calorimetry (DSC) (8, 9).

M_s, A_s transformation temperatures were taken to be those at which a sudden increment in calorimetric signal occurs. The maximum errors are $\pm$ 0.5 K. In the same way the temperatures corresponding to the end of the transformation, M_f and A_f, were determined to be when the calorimetric signal returned to the base line.

Tension tests at room temperatures (20 °C) and body temperature (37 °C) were carried out using an Instron testing machine. In the latter case, the clamps were inside a tank filled with physiological environment at 37 °C.

3. Experimental results and discussion

The transformation temperatures (M_s, M_f, A_s, A_f) were determined from the thermograms obtained: an example is shown in Fig. 1 for the alloy B, for both heating and cooling cycles. These temperatures are given in Table II.

Each of the three alloys studied underwent various cooling–heating cycles and no significant variations were observed in the results. This suggests that heating and cooling cycles does not affect the structural order in the appearance or disappearance of defects that could alter the transformation temperatures.

Chemical composition variations produce large variations in transformation temperatures. For nickel content higher than 50%, transformation temperatures decrease as the nickel content increases [10].

The transformation temperatures show that alloys A and C are austenitic at 20 °C since their M_s is lower than 20 °C. However, alloy B exhibits an austenitic structure with the presence of some martensitic plates, since room temperature lies between M_s and M_f. At 37 °C the three alloys are austenitic.

The stress–strain curve for alloy A can be seen in Fig. 2, showing a total recovery when stress is relieved. This alloy presents an austenitic phase only at test temperatures, showing superelastic behaviour. The

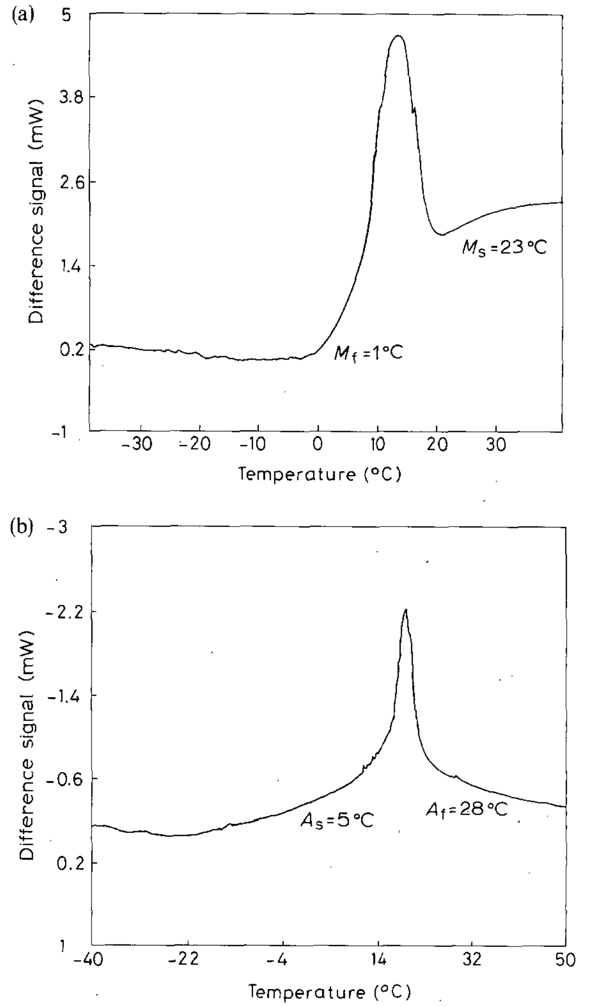

Figure 1 Calorimetric register: (a) cooling cycle; (b) heating cycle.

TABLE II Martensitic transformation temperatures (K)

Alloy	M_s	M_f	A_s	A_f
A	283	264	271	288
B	296	274	278	301
C	285	260	280	289

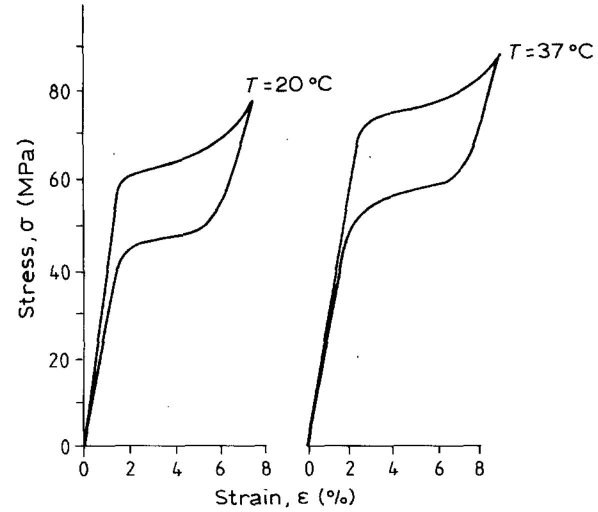

Figure 2 Stress–strain curve for alloy A.

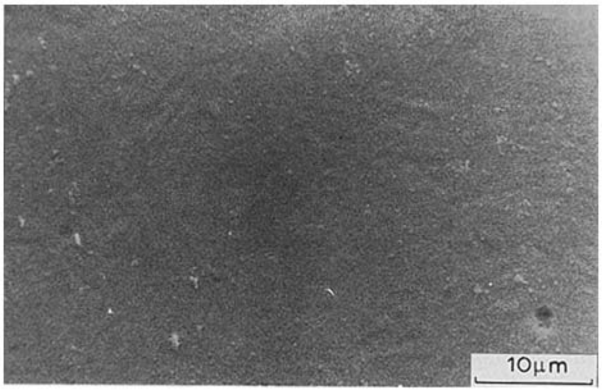

Figure 3 Austenitic microstructure.

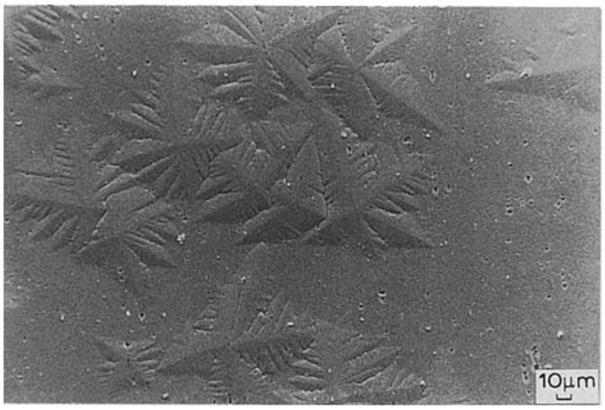

Figure 4 Austenitic + martensitic microstructure.

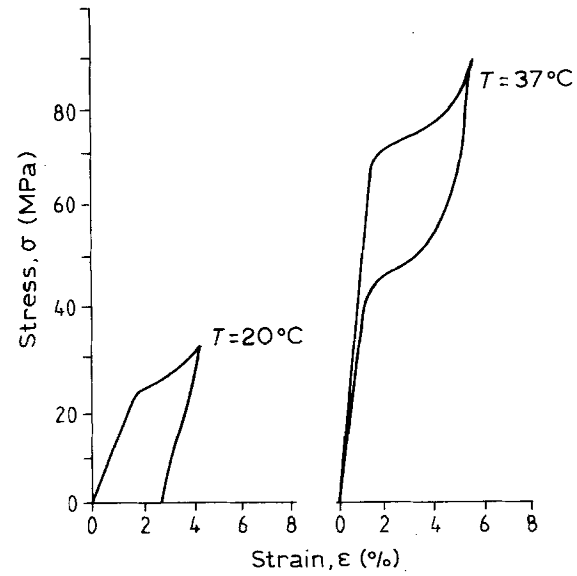

Figure 5 Stress–strain curve for alloy B.

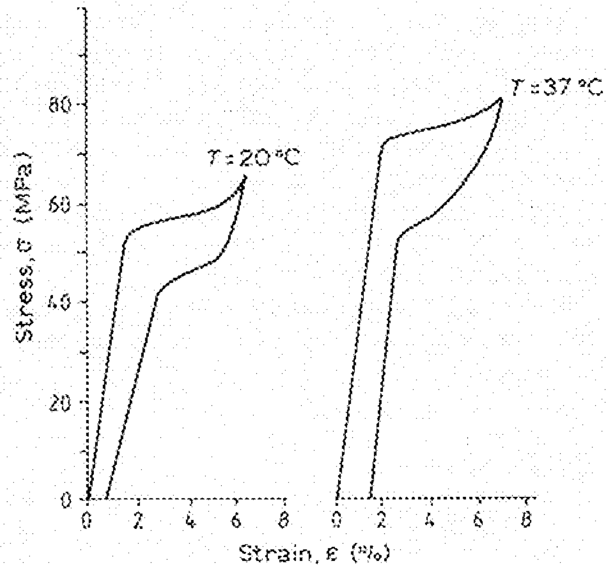

Figure 6 Stress–strain curve for alloy C.

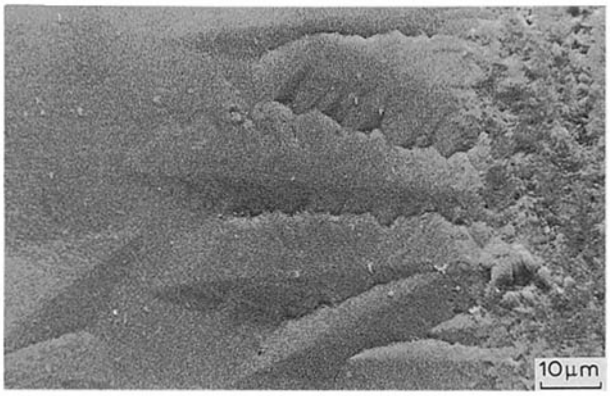

Figure 7 Stress-induced martensite.

TABLE III Transformation and retransformation stresses (MPa)

Alloy	$T = 20\,°C$		$T = 37\,°C$	
	$\sigma^{A \rightarrow SIM}$	$\sigma^{SIM \rightarrow A}$	$\sigma^{A \rightarrow SIM}$	$\sigma^{SIM \rightarrow A}$
A	60	42	76	53
B	23	–	59	43
C	52	42	71	51

microstructure of this sample is shown in Fig. 3. Alloy B with austenitic + martenitic structure at 20 °C (Fig. 4) exhibits a stress–strain curve with partial recovery, as can be seen in Fig. 5. The austenitic phase transforms under stress into martensite, and the original martensite deforms plastically. By heating to the A_f temperature, the alloy recovers its original shape due to the shape memory effect. The structure of this alloy is fully austenitic at 37 °C and therefore its stress–strain diagram is characteristic of a pseudoelastic material.

Alloy C should behave pseudoelastically since, according to its transformation temperatures, the structure should be fully austenitic. However, it can be noticed in its stress–strain diagram that a permanent deformation equivalent to 1% remains, as shown in Fig. 6. This is due to the manufacturing process, in which large deformations have stabilized martensite. These stabilized stress-induced martensitic plates have preferential orientations from the sample surface (Fig. 7); these plates differ from those obtained by heat treatment, which can have several possible self-accommodation variants.

The thermomechanical process in alloy C creates dislocation-type defects which provoke anchorage of the stress-induced martensitic plates; total retransformation is thus avoided.

The results of transformation stress (austenite ⇌ stress induced martensite (A⇌SIM)) are shown in Table III for each alloy and test temperature.

As the temperature increases an increase in stress can be observed. This increase can be explained by the fact that the stability of the austenite phase increases as the temperature increases. The stress has to increase so that the mechanical energy may overcome the increased thermodynamic stability.

It should be stressed that the technological properties of the alloys depend very much on their careful preparation.

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