The Reversion Force of NiTi Orthodontic Wires in the Temperature Domain 5 ÷ 55 °C

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Abstract. The interest in using the pseudoelastic properties of NiTi wires in orthodontic practice arises chiefly from the expectation that they can afford low continuous forces at constant temperature.
The reversion force developed by NiTi archwires depends, however, upon temperature since the superelastic force follows a Clausius-Clapeyron like equation.
Actually the oral environment temperature is modified as a consequence of hot/cold liquid/solid intake in the temperature range 5°- 55°C, as previously evaluated. In the above-mentioned temperature range first results have already been obtained on the reversion force variation.
Attention is focused here on the reversion force as a function of temperature under different fixed constraints. Tensile and 3-point bending tests have been performed on NiTi orthodontic wires, adopted in orthodontic practice, starting at body temperature: loading and partial unloading have been performed in order to fix different constraint conditions corresponding to different states in orthodontic therapy. The variation of the reversion force has been studied as a function of temperature. Evidence has been obtained of the hysteretic behaviour of the reversion force as a function of temperature. The results show that after a temperature loop to high temperature the reversion force is generally changed: the overall shape of the hysteresis cycle appears dominated by the presence of the R-phase at T<37°C and by the stress-induced martensite at T>37°C.

1. INTRODUCTION

The pseudoelastic response of NiTi wires has been exploited in orthodontics in recent years to provide a constant physiological force in the correction of malocclusions [1, 2]. The force developed by NiTi wires remains constant on condition, however, that the oral cavity temperature is constant. In fact, the reversion force depends upon temperature following a Clausius-Clapeyron like law $d\sigma/dT=\Delta H/T \cdot \varepsilon$. Since the ambient oral temperature can be modified as a consequence of hot/cold liquid/solid intake [3] and, even, of phonation, modifications in the pseudoelastic reversion force acting on the teeth are expected during therapy [4, 5]. It seems clear that correct orthodontic therapy cannot be achieved without full knowledge of the evolution of the superelastic force during therapy. Previous results on the superelastic force developed by constrained NiTi wires tested in 3P-B tests in the temperature range 5-55°C have already shown both the great change of the reversion force and the presence of an hysteresis loop. Since the 3P-B configuration implies a complex stress state in the wires with some fibres under tension and others under compression, it is difficult to obtain a clear view of the processes involved. The evolution of the superelastic force is investigated here as a function of temperature under uniaxial tensile tests, at different constraint conditions, in order to simulate different states in the orthodontic therapy.

2. EXPERIMENTAL

Commercial superelastic NiTi alloys (F200 Neosentalloy, kindly provided by GAC International Inc., USA), 0.46×0.64mm² in cross section, were examined.

 Differential Scanning Calorimetry measurements were performed in the range -70°C ÷ +120°C using a Perkin Elmer DSC Lab 7, with a calorimetric sensitivity of ±0.01mW, using a Intracooler II cooling

system. The calorimeter was calibrated using an *ad hoc* calibration method developed for shape memory alloys [6]. A 0.083 °C/sec rate was adopted.

Tensile and Three-Point Bending (3P-B) tests were performed with a ZWICK 1445 testing machine (a 500N load cell was used for tensile measurements; a 100N load cell for 3P-B). Tensile test specimens had a typical gauge length of 100mm. The 3P-B test specimen was 25mm in length with a 14mm span length. A 1.7 x 10^{-4}/sec strain rate was used in tensile tests and a 0.017mm/sec deflection rate in 3P-B tests. Either specimen elongation or deflection was measured via the crosshead·travel monitor, with 1μm resolution. The reversion force was studied in the temperature range 5 ÷55°C at selected deflections or elongations: the test temperature was controlled using a circulating liquid thermostatic chamber equipped with a Lauda RC20 thermostat and monitored using six T-type thermocouples.

3. RESULTS

The DSC curve for one of the investigated specimens is shown in fig. 1a. It appears clearly that the wire investigated undergoes two transformations (P→R and R→M) on cooling with T_r= 20.5 °C , M_s=-23.4 °C, and a single transformation (M→P) on heating with A_s= 16.2°C [5]. In the temperature (T) range of interest, just the P↔R transformation is involved, as shown in fig. 1b ($T_{r(P→R)}$ =20.5°C, $T_{r'(R→P)}$ =17.5°C). At body temperature (37°C) a pseudoelastic stress-strain behaviour is found, as shown in figure 2 for a tensile test.

Figure 3 shows a load deflection 3P-B curve at 37°C. The dots represent the deflection values (1, 2 and 3 mm) selected as the constraint for the force vs. temperature investigations.

The superelastic reversion force variation related to the oral cavity temperature changes was measured following two thermal cycles:
I) 37°C ⇒ 5°C ⇒ 37°C ⇒ 55°C ⇒ 37°C (TC I)

II) 37°C ⇒ 55°C ⇒ 37°C ⇒ 5°C ⇒ 37°C (TC II)

Figure 1 DSC of a NiTi specimen: a) in between -65°c and 45°C; b) in between -5°C and 45°C.

Typical results are shown in fig. 4, where the reversion force vs. temperature is plotted for a fixed deflection of 2 mm, either during TC I (bold line) or TC II (thin line). As previously found [5], an hysteresis loop appears between the reversion force values obtained during TC I and those during TC II. The reversion force related to the stress induced martensite process is clearly involved during the heating step 37-55°C and the non linear behaviour in the range 30-20°C is presumably related to the R-phase. A clear understanding is, however, hampered by the complex stress state distribution existing in a 3P-B test specimen.

Uniaxial tensile tests, where a uniform stress state exists, were undertaken with the same philosophy to reach a clear view of the processes involved. In this case the reversion force was detected either during TC I or during TC II for fixed displacements of 1, 1.5 and 2 mm on unloading (corresponding respectively to 1, 1.5, 2 % strain), indicated by the dots on the curve in fig. 2. The results obtained are shown in figs. 5-
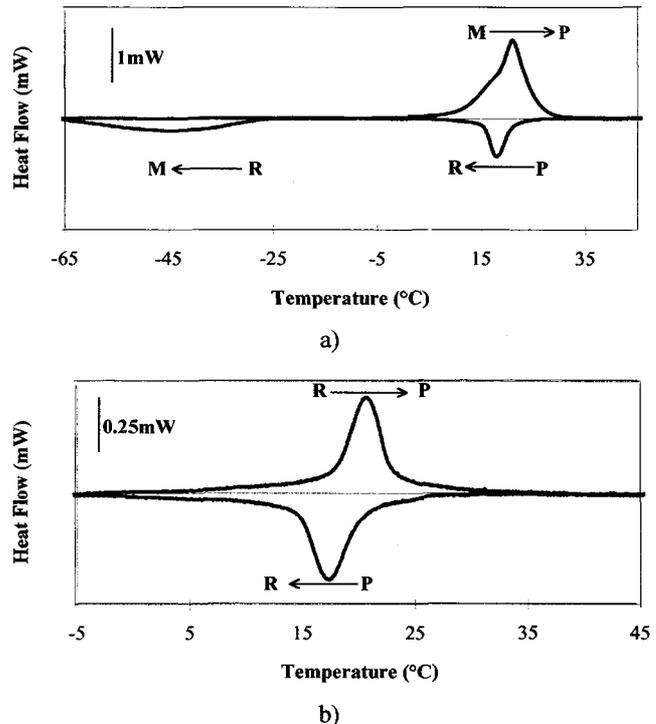
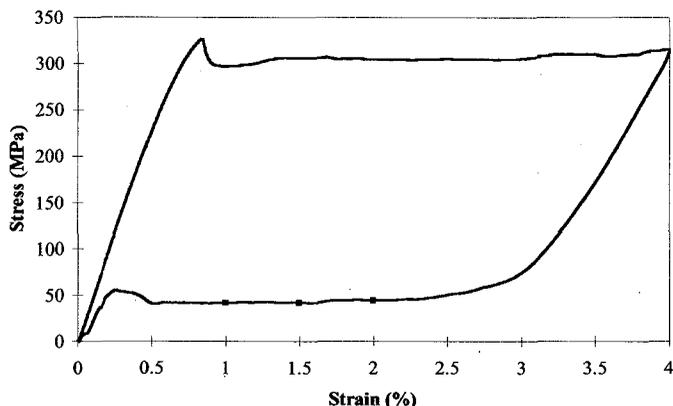**Figure 2** Stress-strain in a uniaxial tensile text at T=37°C. The dots represent the fixed displacements selected as constraint.

7: in the upper part of each figure the reversion stress values developed during TC I are plotted, in the lower part those developed during TC II.

4. DISCUSSION

As already found in 3P-B tests, for all investigated constraints, the reversion force exhibits an hysteresis loop as a function of temperature: during TC I the reversion force decreases with T in the range 37°C ⇒ 5°C. In the branch 5°C ⇒ 37°C ⇒ 55°C the reversion force increases with increasing T, following distinct paths: beyond the region of the R↔P transformation, it increases slightly up to 37°C and then increases linearly with T. On cooling from 55°C, a plain decrease is found down to 37°C.

In TC II the reversion force increases linearly with T in the range 37-55°C, as found in TC I in the same range of T; a plain decrease follows down to the temperature range where the R-phase can set in. In the temperature range 20°C - 30°C a small hysteresis (ΔT≈ 1.5°C) appears between the branch on heating with respect to that on cooling .

The reversion force at 37°C, for fixed constraint, is not modified as a consequence of a thermal cycle at low temperatures (37°C ⇒ 5°C ⇒ 37°C), whilst it is drastically modified as a consequence of a thermal cycle at high temperatures
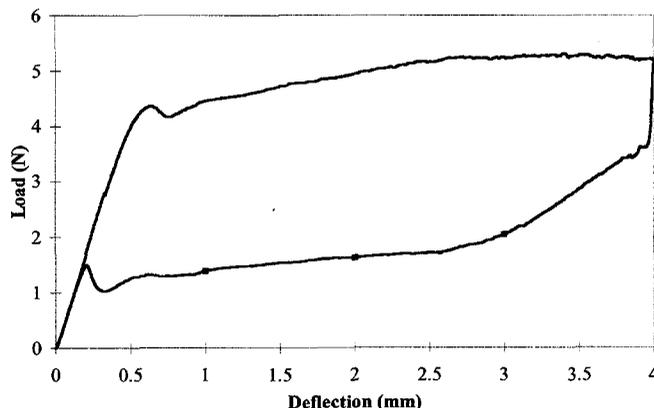

Figure 3 Load-deflection in a 3P-B test at 37°C. The dots represent the deflection values selected as constraint.

(37 ⇒ 55°C ⇒ 37°C): once the constraint is relaxed, the reversion stress follows the usual unloading path, after a transient displacement region, as shown in fig. 8.

As for the rate of change of the reversion stress with T, three distinct ranges are evident:

1) 15 - 30°C either on heating or on cooling;

2) 37 - 55°C on heating;

3) the regions in between, one in between 30-37°C, either on heating or on cooling, and the other in between 55 - 37°C on cooling.

The rates of change of the reversion stress are calculated by a best fit to the data as shown in fig. 9: the figures related to the above indicated ranges are given in table 1, for all the investigated conditions.

In the first range, values between 8.3÷10.7 MPa/°C are found in TC I (table 1, columns b, c), whilst ≈12.5 MPa/°C is found for TC II (table 1, columns c, e): in the first case the range of temperatures involved, 15.5 ÷ 22 °C on cooling and 16.3 ÷ 24.0 °C on heating, is slightly lower than the second case where the temperature range involved is 18 ÷ 30°C on cooling and 19 ÷ 31.5°C on heating.
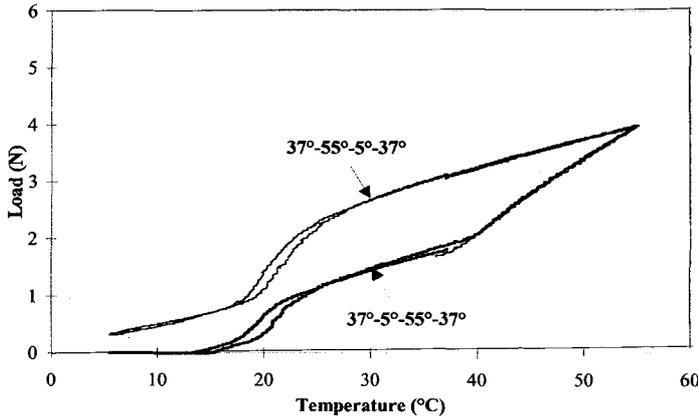
Figure 4 Reversion force vs. temperature in a 3P-B test for a fixed deflection of 2mm (TC I bold line; TC II thin line).

The start and finish transformation temperature ranges are given in table 2. Both the rate of change of the reversion stress with temperature and the range of temperatures involved, higher than A_f temperature, support the hypothesis the P$\Leftrightarrow$R transformation is stress induced [7, 8].

As for range 2), $37 \div 55°C$, the reversion stress rate of change, ≈ 8 MPa/°C (see table 1, col. a, d), appears clearly related to the M$\Rightarrow$P stress-induced transformation [7, 8]: it appears worth noting that the martensite fraction present at 37°C is higher than the fraction present at 55°C.

In region 3), $30 \div 37°C$, the reversion stress rates of change appear definitely low (see table 1, col. a) though significantly different between the different cases examined: 1, 1.5, 2 mm fixed deflection. The same remark applies to the reversion stress rate of change in the temperature range 37 -55°C on cooling (see table 1, col. e). The figures for the rate of change of the reversion stress in these temperature domains appear to be connected with the martensite fraction: the higher the martensite fraction, the higher the rate of change for the reversion stress.
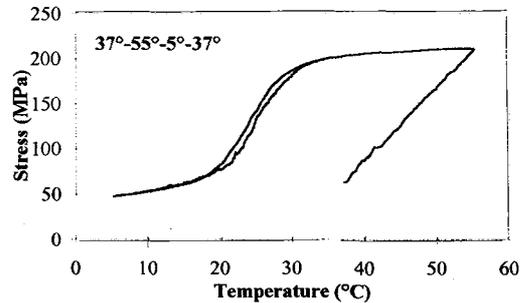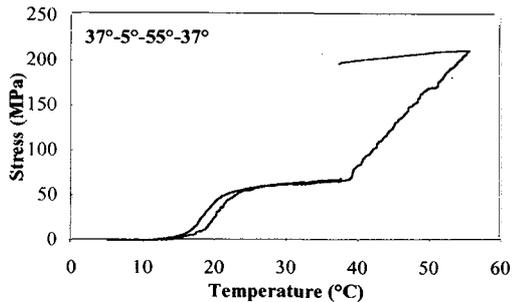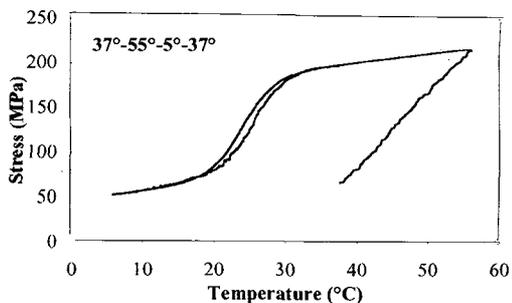

a)
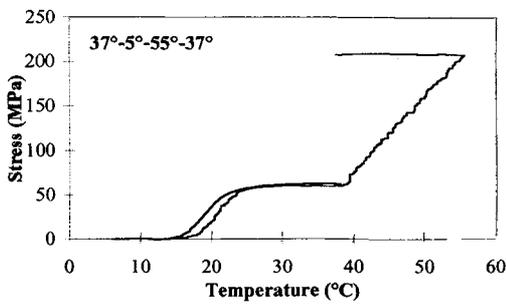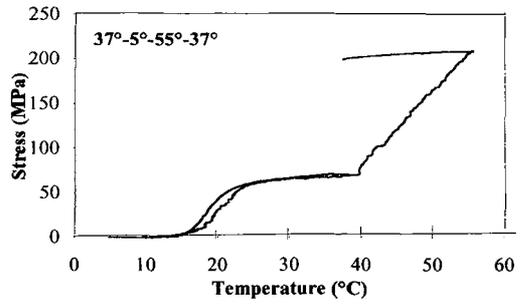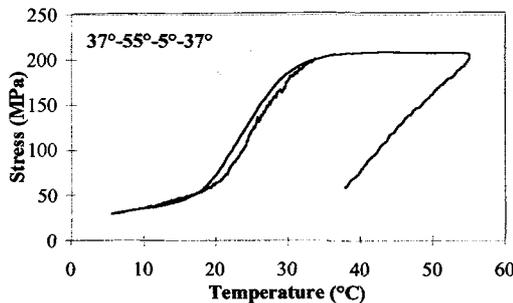
b)

Figure 5 Reversion stress vs. temperature for a fixed displacement of 1mm: a) TC I; b) TC II.

a)

b)

Figure 6 Reversion stress vs. temperature for a fixed displacement of 1.5mm: a) TC I; b) TC II.

a)

b)

Figure 7 Reversion stress vs. temperature for a fixed displacement of 2mm: a) TC I; b) TC II.
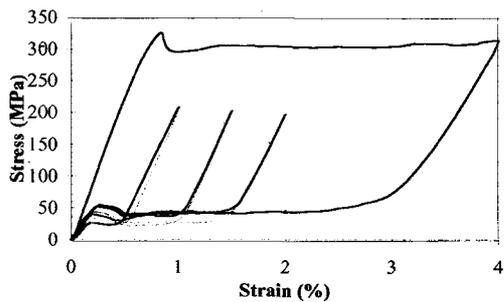

Figure 8 Stress-strain in a uniaxial test at 37°C: the reversion stress when the constraint is relaxed is also shown after TC I (thin line) and TC II (bold line).
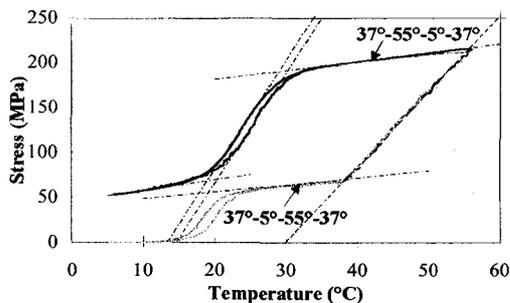

Figure 9 Reversion stress vs. temperature for a fixed constraint during either TC I or TC II: best fits of the rate of change are also indicated for some distinct ranges.

Table 1 Reversion stress rates in all the selected ranges of temperature.

	dσ/dT (MPa/°C)				
	a	**b**	**c**	**d**	**e**
Thermal Cycle I					
Temperature range	37°C-30°C	30°C-15°C	15°C-30°C	37°C-55°C	55°C-37°C
	Cooling	Cooling	Heating	Heating	Cooling
Constraint (mm)					
2	0.79	9.58	10.65	8.35	0.86
1.5	0.58	9.81	8.25	8.4	0.52
1	0.02	8.53	8.87	8.41	0.01
Thermal Cycle II					
Temperature range	37°C-55°C	55°C-37°C	30°C-15°C	15°C-5°C	15°C-30°C
	Heating	Cooling	Cooling	Cooling	Heating
Constraint (mm)					
2	8.37	1	12.17	1.18	12.25
1.5	8.11	0.56	12.99	1.27	12.51
1	7.91	0.05	12.73	1.39	11.93

Table 2 Start and finish transformation temperatures.

Thermal Cycle I				
	Cooling		Heating	
Constraint (mm)	T start (°C)	T finish (°C)	T start (°C)	T finish (°C)
2	21.31	15.36	17.34	22.8
1.5	21.81	15.46	16.26	23.97
1	22.76	15.73	17.61	24.37
Thermal Cycle II				
	Cooling		Heating	
Constraint (mm)	T start (°C)	T finish (°C)	T start (°C)	T finish (°C)
2	28.93	18.92	20.32	30.23
1.5	29.37	19.06	19.96	30.63
1	29.86	18.04	18.96	31.54

5. CONCLUSIONS

The reversion force of NiTi orthodontic wires has been measured for fixed constraints, as a function of thermal cycles within the range of temperatures 5 $\Rightarrow$ 55°C.

Both in 3P-B and uniaxial tests, the reversion force is modified with temperature: however, it recovers the starting value at 37°C after a low-temperature cycle to 5°C, whilst it changes drastically after a high-temperature cycle to 55°C.

The linear reversion force modification in the temperature range 37-55°C is related to the P $\Rightarrow$ M stress induced transformation.

The non-linear reversion force modification with temperature in the temperature range 15 $\div$ 30°C is related to the R $\Leftrightarrow$ P stress-induced transformation, whilst the plain modifications within the ranges 30 $\div$37°C or 55 $\div$ 37°C appear related to rearrangements of martensitic variants.

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