THE EFFECT OF CYCLIC BENDING STRAINS ON THE BEHAVIOR OF SUPERELASTIC NICKEL-TITANIUM WIRES AND ENDODONTIC INSTRUMENTS

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ABSTRACT

Cyclic bending strains with a maximum amplitude of approximately 5% are developed when NiTi endodontic instruments are clinically employed for preparing curved root canals using the rotary technique. The effect of these high amplitude cyclic strains on the behavior of NiTi superelastic alloys is not yet fully understood. The aim of this work was the evaluation of the influence of this type of deformation on the martensitic and reverse transformation temperatures of a wire of superelastic NiTi and on the mechanical properties in torsion of NiTi ProFile endodontic instruments. Cyclic bending tests were performed employing three different radius of curvature, to allow maximum tensile strain amplitudes of 2.0, 3.0 e 4.5% at the wire surface. The martensitic and reverse transformation temperatures of the wires before and after cyclic straining to 1/2 and 3/4 of their fatigue life were determined by differential scanning calorimetry. Similarly, the NiTi endodontic instruments were tested in fatigue in a device simulating the geometric conditions found in the clinical practice to 1/2 and 3/4 of their fatigue life. Considerable changes in the martensitic and reverse transformation temperatures were detected in the wires strained to 4.5%, indicating the tendency of martensite stabilization during mechanical cycling, which was independent of the number of cycles. In agreement with this result, the values of maximum torque and angular deflection of NiTi instruments were strongly influenced by the previous cyclic bending deformation, but their behavior seems to be independent of the previous number of cycles. This is an indication that fatigue of NiTi alloys in the superelastic regime involves rapid nucleation and slow propagation of fatigue cracks.

1 INTRODUCTION

Nickel-titanium alloys with approximately the equiatomic composition are well known for their excellent shape memory and superelastic properties and are widely used in a number of applications. The main concern about these properties has been their stability under temperature changes or prolonged exposure to the human body temperature. The fatigue behavior of the material under high amplitude cyclic strains has not received appropriate attention, since it was not an important concern. However, the development of machine driven endodontic files made of NiTi superelastic wires, which has greatly simplified the preparation of root canal systems, by maintaining the shape and position in space of the apical foramen, gave rise to relevant questions regarding this behavior. This is because cyclic bending strains with a maximum amplitude of approximately 5% are developed when NiTi endodontic instruments are clinically employed for preparing curved root canals using the rotary technique. The influence of the amplitude of the tensile strain component developed at the surface of NiTi wires submitted to cyclic bending strains was studied by Tobushi [1], who verified that when the strain amplitude is greater than 1.0% the number of cycles to failure is smaller than 10^4. For strains below 0.8%, the same authors found that the number of cycles to failure is greater than 10^7. Yang [2] and other authors (Suzuki [3] and Tobushi [4]) found that the fatigue behavior of NiTi alloys depend on the type of stress induced transformation taking place during mechanical cycling. The highest fatigue resistance observed in NiTi superelastic alloys is associated with the stress induced martensitic transformation of the metastable β-phase to the R-phase. Nevertheless, this stress induced martensitic transformation takes place only at small tensile strains. The strain amplitudes involved in the endodontic application of NiTi superelastic alloys to format curved root canals are far beyond the values associated with the R-phase formation.

The aim of the present work was to evaluate how cyclic bending loading in the superelastic regime influences the physical and mechanical properties of superelastic NiTi alloys. Transformation temperatures of the superelastic NiTi wires and the mechanical properties in torsion of NiTi endodontic instruments were the parameters analyzed.

EXPERIMENTAL PROCEDURE

The NiTi wires used in this work were acquired in the international market under specification of mechanical behavior and transformation temperatures. Cyclic bending tests were performed employing three different radius of curvature, to allow maximum tensile strain amplitudes of 2.0, 3.0 e 4.5% at the wire surface. The martensitic and reverse transformation temperatures of the wires before and after cyclic straining to 1/2 and 3/4 of their fatigue life were determined by differential scanning calorimetry – DSC (Shimadzu DSC 60, Kyoto, Japan). The endodontic instruments (ProFile, Dentsply-Maillefer,Baillagues, Switzerland) used to evaluate the torsion properties were obtained from the regular suppliers, withdrawn from sealed boxes and sequentially numbered on the handle. The analyzed sample consisted of ten sets of new files identified by their size and taper. Three sizes were employed: 20, 25 and 30. These numbers correspond to the diameter of the instrument's tip, in tenth of millimeters. Taper, or conicity, is a parameter indicating how the diameter of the instrument changes from the tip upwards its active length. Two tapers were employed: 0.04 and 0.06, meaning that the instruments diameter increased by 4% or 6% in each millimeter of their length. A total of 120 instruments were employed, ten of each size and taper, as follows: 20/.04, 25/.04, 30/.04, 20/.06, 25/.06 and 30/.06. These files were submitted to interrupted fatigue tests in a laboratory device to 1/2 and 3/4 of the their number of cycles to failure. The tensile strain amplitude at the instrument's surface lied between 3.3 and 5.0%. Their behavior in torsion was evaluated in a torsion test device specially developed to register the small values of torque they can withstand.

The fatigue test device in which the ProFile instruments were tested was designed so that the maximum strain amplitude is concentrated at 3mm of the tip of the instrument. The torsion tests followed specification number 28 of the American Dental Association, according to which the instruments are fixed at 3mm from their tips. Thus, because of the files conicity, torsion strains were concentrated at the same region submitted to the maximum strain amplitudes in the interrupted fatigue tests.

RESULTS AND DISCUSSION

The average number of cycles to failure, NCF, of the wires tested in fatigue is plotted in Figure 1 against the estimated values of the tensile strain component at the wire surface. These strain values, ε_T, were calculated based on the wire diameter, D, and on the bending curvature radius, R, by means of the expression $\varepsilon_T = 1/[(2R/D) - 1]$, which can be easily deduced from geometrical considerations, taking into account that R reefers to the radius of curvature measured at the outer surface of the bent wire. The variation of NCF with ε_T corresponds to what should be expected for low cycle fatigue controlled by strain. Nevertheless, one should observe that the values of the tensile strain component are very high, showing the excellent fatigue resistance of the NiTi superelastic wires under conditions which the majority of metallic materials could not withstand.

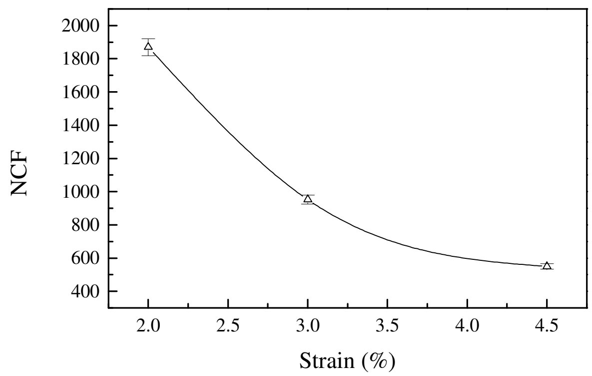


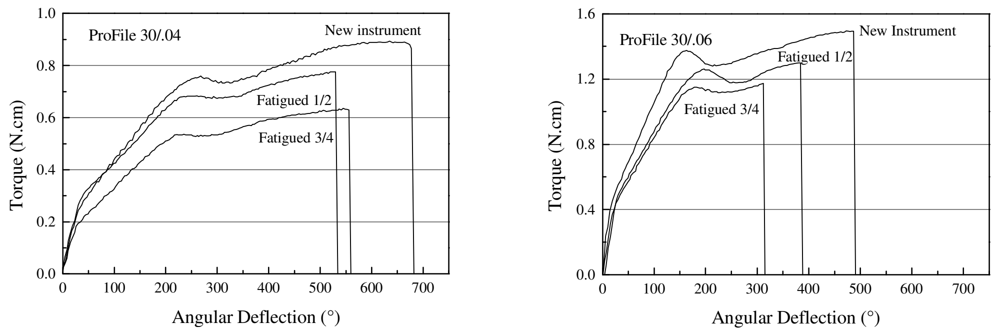
Figure 1: Change in the NCF with the estimated tensile strain component.

The transformation temperatures measured by DSC in wire specimens after interrupted fatigue tests to 1/2 and 3/4 of their fatigue life, for the three levels of tensile strain component considered, are shown in Table 1, together with the values obtained for the wire in the as received condition. The relative maximum error in these measurements was smaller than 2%. It is worth noting that only for the wires strained by 4.5% the transformation temperatures changed significantly. Moreover, the values presented in Table 1 show that the change in the transformation temperatures of these wires is not influenced by the previous number of cycles they suffered, specially at 4.5% strain. This is an indication that NiTi superelastic alloys cyclic strained in the superelastic regime suffer submicroscopic changes that soon tend to saturation.

Table 1: Average values of the transformation temperatures of wires submitted to interrupted fatigue tests.

Specimen		M_S (°C)	M_F (°C)	A_S (°C)	A_F (°C)
As-received		24.4	-27.5	-10.6	23.8
2.0%	1/2	22.6	-26.3	-11.1	23.9
2.0%	3/4	23.7	-26.4	-10.8	24.4
3.0%	1/2	22.9	-27.2	-10.3	24.9
3.0%	3/4	23.5	-25.1	-11.2	25.5
4.5%	1/2	37.8	-12.8	01.8	45.6
4.5%	3/4	38.4	-13.2	02.1	46.1

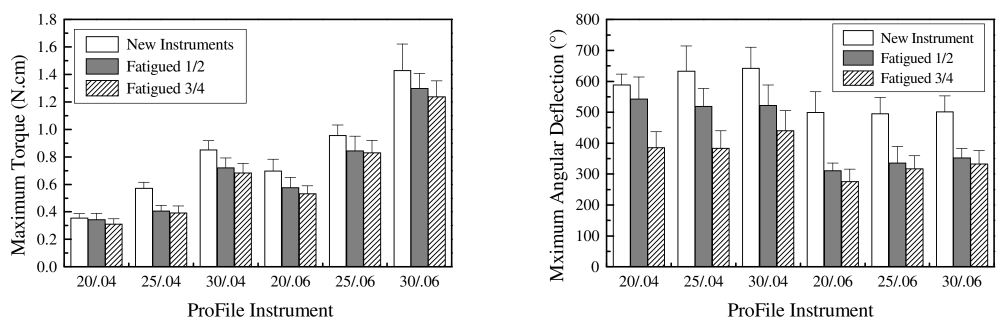
The behavior in torsion of the ProFile instruments previously submitted to interrupted fatigue tests to 1/2 and 3/4 of their fatigue life is illustrated in Figure 2, while in Figure 3 the changes in the average torque to failure and maximum angular deflection are summarized, in comparison with the parameters measured in new instruments.



(a) (b)

Figure 2: Torque and angular deflection of ProFile instruments (a) 30/.04 and (b) 30/.06 tested in torsion.

Comparison of the values of maximum torque and angular deflection measured in the torsion tests of ProFile instruments previously fatigued to 1/2 and 3/4 of their fatigue life, using the Student t test, showed that there is no statistically significant difference ($p < 0.05$) between these parameters. This means that the amount of cyclic strain previously applied to the endodontic NiTi instruments gave rise to the same changes in their torsion behavior. This observation is in agreement with the results found for the changes in the transformation temperatures of NiTi superelastic wires previously submitted to cyclic deformation (Table 1). Both results are coherent with the fact that fatigue crack initiation in NiTi superelastic wires takes place at the beginning of cyclic loading. The relatively high values of the number of cycles to failure measured in high strain fatigue tests of this material are associated with the stage II of fatigue, that is, with the slow propagation of fatigue cracks.



(a) (b)

Figure 3: Maximum torque to failure and maximum angular deflection of ProFile instruments tested in torsion.

Lower fatigue crack propagation rates were observed by McKelvey [5] in martensitic NiTi alloys, in comparison with stable and superelastic austenite. Similarly, Tabanli [6] found that the fatigue life of NiTi was shorter in the region of the superelastic plateau, as a consequence of the coexistence of austenite and martensite. These and other results found in the literature suggest that superelasticity does not increase the resistance to fatigue crack grow in superelastic NiTi alloys (Dauskardt [7]).

However, an important parameter in the analysis of fatigue crack propagation in superelastic NiTi alloys is the multiple nucleation of fatigue cracks at martensite variants and twin borders. The rapid nucleation of numerous fatigue cracks at these sites requires a great number of fatigue cycles in order that macroscopic cracks develop and propagate, leading to the final rapid ductile rupture of the material.

CONCLUSIONS

The results obtained in this work showed that the physical and mechanical properties of superelastic NiTi wires and endodontic instruments suffer great changes due to previous cyclic straining in the superelastic regime. However, these changes are independent os the number of cycles, indicating that the changes in the materials substructure tend to stabilize after a few deformation cycles, showing that fatigue of NiTi alloys in the superelastic regime involves rapid nucleation and slow propagation of fatigue cracks.

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