ROTARY FATIGUE LIFE OF NITI ALLOY WIRES AND FEA MODELLING OF FATIGUE DAMAGE

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ABSTRACT

Nickel-Titanium (NiTi) alloys with superelastic properties have been increasingly introduced as a substitute to more conventional alloys. For example, NiTi alloys used in Dentistry, such as in Endodontic rotary files, possess superelastic properties that allow for the file to follow teeth root canals more easily than their stainless-steel counterparts. Nevertheless, during surgery, the file is subjected to cyclic bending loading, since it is spinning while being deformed inside the curved canal. Therefore, these instruments are prone to fracture due to fatigue, without showing any visible signals of degradation. This problem brought new challenges on how new instruments should be tested, as NiTi alloys are highly non-linear. However, most existing test setups ignore the fracture mechanics involved in the fatigue phenomenon. In this work, the results of rotary fatigue tests for NiTi wires from different manufacturers is presented. The formulation is described, where the material strength reduction can be quantified from the determination of the strain and the number of cycles until failure. Experimental tests as well as numerical Finite Element Analysis (FEA) simulations are presented to better understand the fatigue fracture mechanisms present in NiTi alloys, showing that there is good agreement between the predicted strains (difficult to measure in such small wires) and the cycles to failure. One characteristic is that these alloys exhibit a large hysteresis in the elastic domain if loaded up to the mixture of austenitic and martensitic phases (also known as B19’ martensite) and then unloaded. Rotating bending fatigue tests of NiTi wires show that, when loaded up to the B19’ martensite, the number of cycles to failure decrease with the applied strain.

KEYWORDS

Endodontic files, NiTi alloys, Rotary bending fatigue, Finite Element Analysis

INTRODUCTION

In dentistry, the root canal treatment consists of removing the tooth’s pulp using an endodontic file. In the past, these instruments were made from stainless steel alloys. However, steel alloys, while being flexible, are still too stiff to avoid damaging the walls in the root canals. These adverse effects can be minimised by using Nickel-Titanium (NiTi) alloys in the design of endodontic rotary files. NiTi alloys have ‘superelastic’ properties, hence the files are able to fully recover from large deformations (up to strains of 10% [1]). These alloys, however, have some limitations when compared to steel: their fatigue life is relatively shorter and they can break without a visible mechanical warning (e.g., plastic deformation), increasing the risk of failure inside the root canal.

There are some studies to determine the fatigue life of NiTi alloys, through traditional uniaxial fatigue tests and rotary bending fatigue tests [2]. Rotary bending are the tests that most accurately replicate the loads and deformations a file is subjected to when inside a root canal. Of special interest is the rotary fatigue machine designed by Cheung and Darvell [3]. This machine consists of three pins that can be positioned manually to deform the endondontic file. The file is then put into rotation using a contra-angle. This type of machine has the advantage of being more versatile than the more common machines that use predetermined simulated canals carved in, e.g., stainless steel plates, which can only deform the files with predetermined and less complex curvatures [4, 5, 6, 7].

In this work, an automated configurable rotary bending-testing machine is presented. This testing machine was designed to adapt and change the degree of bending from simple point bending to more complex multi-point bending. The machine consists of three pairs of pins positioned by servomotors, which deform the specimen into a desired complex shape. The specimen is then put into rotation until failure is detected. Therefore, the machine design also enables rotary bending tests to be conducted with constant curvature (constant strain) along a segment. Within this formulation, results can be compared with the more common uniaxial fatigue tests. Also, one can perform tests in different regions of the superelastic stress-strain curve, enabling an estimation of the stress and the crystallographic phase of the alloy during the test. However, due to the very small diameter of the wire used to manufacture the files (usually smaller than 1mm), it is not possible (or, at least, it would be very difficult) to directly measure the actual strain imposed to the specimen under test. Therefore, Finite Element Models (FEM) must be used.

TESTING MACHINE

The testing machine was designed to be versatile and to offer a wide range of possible bending configurations. Based in the machine designed by Cheung and Darvell [3], the testing machine has three pins that can be configured to make 1 to 4 point bending tests. Configurable positioning enables greater precision and repeatability, providing a simple interface, (Fig. 1).

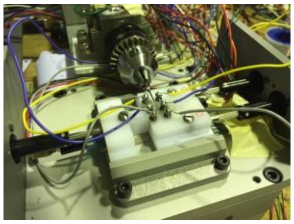


Fig. 1: Rotary bending fatigue testing machine with an endondontic file.

The three relative and optimal pin displacements are obtained using a standard square minimisation algorithm. This is done in order to achieve the desired constant strain level in the specimen midsection, while the overall deformation is minimised and in such a way that the wire is tangent to the pins at all times [8]. This leads to a variable distance between the contact point at the surface and the neutral surface [8]. Adding this requirement to the optimization algorithm, deformation profiles like the one in Fig. 2 are obtained.

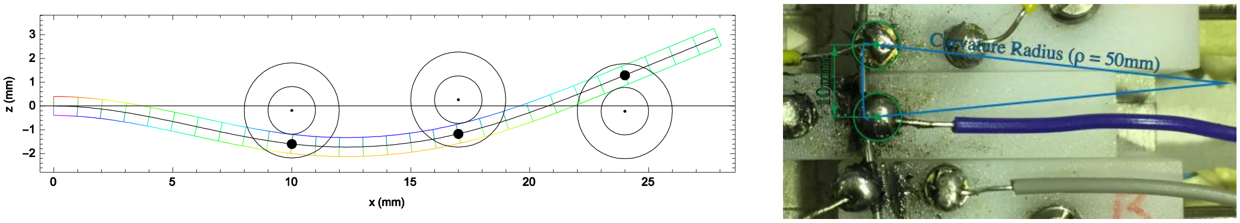


Fig. 2: Beam under a desired constant strain of 2%, with color-coded strain and tangent pins. The contact is maintained by the elasticity of the wire and it is directly proportional to the amount of deformation.

EXPERIMENTAL RESULTS FOR NITI WIRES

The first materials to be tested in the rotary bending fatigue machine were Memry™ and Euroflex™ wires, both with a diameter of 0.8mm. The wires, when under a uniaxial load, have the stress-strain relation in Fig. 3.

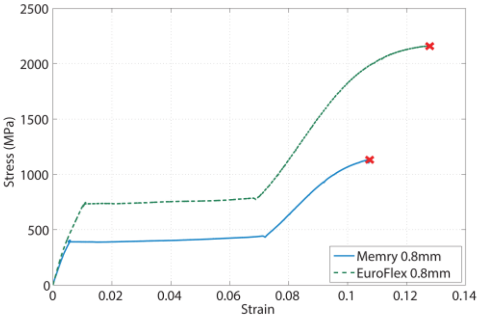


Fig. 3: Uniaxial tensile test of the Memry™ and Euroflex™ 0.8mm diameter wires.

Fig. 3 has three distinct regions: a first austenitic elastic region, a horizontal elastic region with a mixture of austenitic and martensitic phases (also known as B19' martensite) and a final plastic martensitic region. Another characteristic of these NiTi alloys is that they exhibit a large hysteresis when unloading occurs.

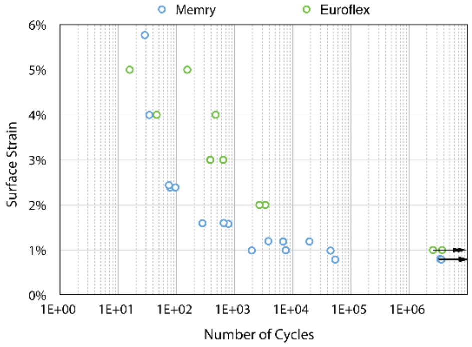
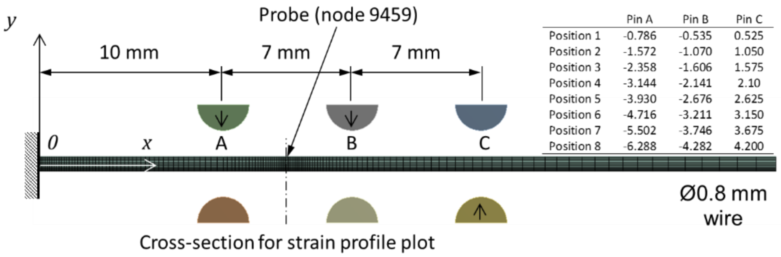


Fig. 4: Strain vs. number of cycles for the Memry™ and Euroflex™ 0.8mm diameter wires.

The fatigue tests were concentrated on the first two regions, imposing theoretical strain levels from 0.8% to 6%. The results can be seen in Fig. 4. The specimens with strains smaller or equal to 1% (corresponding to the first zone in the stress-strain plot in Fig. 3) show a large fatigue life (and up to infinity) when compared with the rest of the points. The remaining points show a decrease of the fatigue life as the imposed strain increases. The specimen with the largest strain showed a life of 34 cycles for the Memry™ wire and 16 cycles for the Euroflex™ wires.

NUMERICAL RESULTS

A cyclic structural FEA was conducted in ANSYS® Workbench. The 0.8mm diameter wire was modelled with a 11760 Hexahedral mesh with bias (Fig. 5) and superelastic material properties [8, 9, 10]. The three steel actuator pins A, B and C move in the *y* direction up to eight considered different positions, where pin C is out-of-phase with respect to pins A and B.



	Pin A	Pin B	Pin C
Position 1	-0.786	-0.535	0.525
Position 2	-1.572	-1.070	1.050
Position 3	-2.358	-1.606	1.575
Position 4	-3.144	-2.141	2.10
Position 5	-3.930	-2.676	2.625
Position 6	-4.716	-3.211	3.150
Position 7	-5.502	-3.746	3.675
Position 8	-6.288	-4.282	4.200

Fig. 5: Mesh (biased), boundary conditions and loads (displacements) for the FEA model.

Taking as an example the Euroflex material, the wire's deformation for position 5 is shown in Fig. 6, where the maximum strain (hence, the maximum stress) occurs between pins A and B and is approximately constant between these two locations, as intended. Fig. 7 shows the normal stress vs strain plots for different pins' positions at a nodal probe (node 9459 in Fig. 5), where position 1 does not impose sufficient deformation for the B19' transformation to take place. Fig. 8 shows the normal stress and strain across the wire's cross-section for different positions.

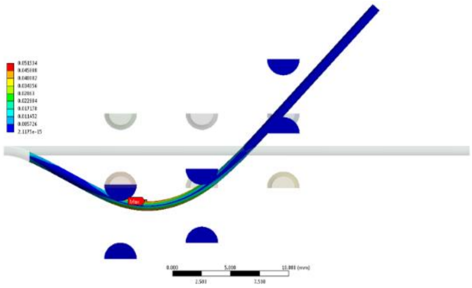


Fig. 6: Illustrative equivalent strain distribution and deformation of the file at position 5.

Fig. 7 shows that the behaviour of the alloys is non-linear and that there is a very high hysteresis during a cycle of deformation, which is expected for a superelastic alloy. Since sustained hysteresis is a necessary condition for fatigue and is related to the rate of damage accumulation [11] and since the higher the imposed strain the higher the energy dissipation is (from Fig. 7), it is reasonable to assume that strain can be better correlated with fatigue in NiTi materials rather than stress, as the latter is almost constant during the B19' phase. It should also be noted that the alloy is deforming elastically in Fig. 7 as its original shape is completely restored after the load is removed. Another observation is that, from Fig. 8, once the most stressed fibres reach the B19’ phase, the stress is distributed across the wire’s cross-section rather than increasing, so the wire is always behaving elastically between pins A and B up to position 8. This reinforces the importance of using the strain as a fatigue indicator for NiTi alloys, rather than stress.

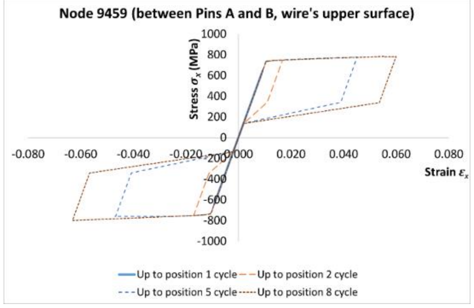


Fig. 7: Normal stress vs strain at a node located between pins A and B for different loading conditions.

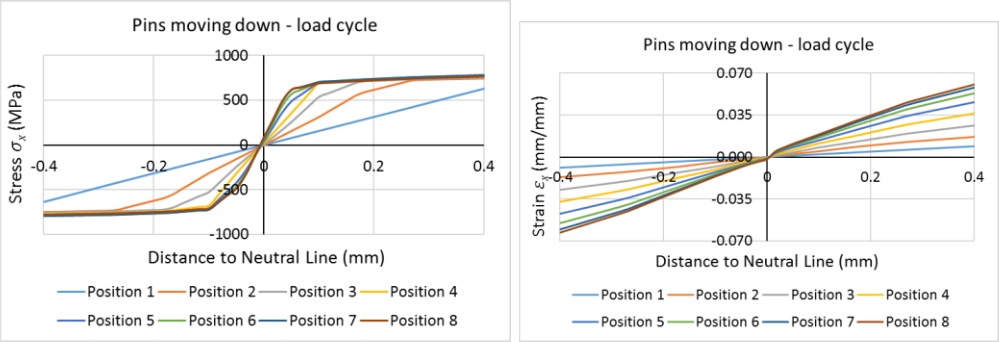


Fig. 8: Equivalent strain distribution and deformation of the file at position 5.

CONCLUSIONS

A testing apparatus designed to perform rotary fatigue tests on NiTi endondontic files under different loading conditions was designed, is versatile and enables a series of different testing configurations, from loading to deformation conditions. Computer controlled automatic positioning of a system comprised of three pins is used to bend the specimens into many users specified shapes. A combination of analytical and numerical models allows determining the strain (and stress) levels at different locations of the NiTi wires. This would otherwise be very hard to measure due to the wires’ thickness (usually smaller than 1 mm). Fatigue tests were done using a Memry and Euroflex 0.8mm diameter wires. A bending configuration that has a constant maximum strain section was imposed, allowing for S-N curves to be plotted.

The wires showed a long fatigue life (most of the specimens did not fail) when under strain levels in the elastic austenitic phase. When imposing strains in the B19’ martensitic region, the fatigue life of the wire drastically reduced, with fatigue life ranging from 20 000 (lower strain levels) to 16 cycles (higher strain levels). At this crystallographic phase, even if the change in stress is very small with the changed in deformation, it is the high hysteresis that is governing the fatigue damage accumulation. Thus, the strain (or the released energy) appears as a better indicator of the fatigue life rather than stress.

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REFERENCES

[1] S. W. Robertson, A. R. Pelton and R. O. Ritchie:
Mechanical fatigue and fracture of Nitinol
International Materials Reviews, vol. 57 (2012), pp. 1-36.

[2] G. Plotino, N. M. Grange, M. Cordaro, L. Testarelli and G. Gambarini:
A Review of Cyclic Fatigue Testing of Nickel-Titanium Rotary Instruments
Cyclic Fatigue or Rotary Instruments, vol. 35 (2009), pp. 1469-1476.

[3] G. S. P. Cheung and B. W. Darvell:
Fatigue testing of a NiTi rotary instrument. Part 1: strain-life relationship
International Endondontic Journal, vol. 40 (2007), pp. 612-618.

[4] G. Plotino, N. M. Grange, M. C. Melo, M. G. Bahia, L. Testarelli and G. Gambarini:
Cyclic fatigue of Niti rotary instruments in a simulated apical abrupt curvature
International Endondontic Journal, vol. 43 (2010), pp. 226-230.

[5] H. P. Lopes, I. M. O. Britto, C. N. Elias, et al:
Cyclic fatigue resistance of ProTaper Universal instruments when subjected to static and dynamic tests
Oral Surg Oral Med Oral Pathol Oral Radiol Endod vol. 110 (2010), pp. 401-404.

[6] G. Gambarini, R. Gergi, A. Naaman, N. Osta and D. A. Sudani:
Cyclic fatigue analisys of twisted file rotary NiTi instruments used in reciprocating motion
International Endondontic Journal vol. 45 (2012), pp. 802-806.

[7] G. De-Deus, E. J. L. Moreira, H. P. Lopes and C. N. Elias:
Extended cyclic fatigue life of F2 ProTaper instruments used in reciprocating movement
International Endondontic Journal, vol. 43 (2010), pp. 1063-1068.

[8] A. Carvalho, M. Freitas, D. Montalvão and M. Fonte:
Rotary Fatigue Testing to Determine the Fatigue Life of NiTi alloy Wires: An Experimental and Numerical Analysis
Procedia Structural Integrity, vol. 1 (2016), pp. 34-41.

[9] A. Carvalho, M. Freitas, L. Reis, D. Montalvão and M. Fonte:
Rotary Fatigue Testing Machine to Determine the Fatigue Life of NiTi alloy Wires and Endondontic Files
Procedia Engineering vol. 114 (2015), pp. 500-505.

[10] W. Yin, F. Sczerzenie, M. Long, C. Belden, R. M. Manjeri and R. Lafond:
Structure and Properties of Large Diameter Hot Rolled NiTi Bars for Seismis Applications
SAES Smart Materials, New Harthford, New York, 2015.

[11] T. Erber, S. A. Guralnick and S. C. Michels:
Hysteresis and Fatigue
Annals of Physics, vol. 224, pp. 157-192, 1993.

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