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Rotary Fatigue Testing Machine to Determine the Fatigue Life of NiTi alloy Wires and Endondontic Files

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Abstract

Endodontic rotary file instruments used to treat root canals in dentistry suffered breakthrough transformations in recent years when stainless steel was replaced by Nickel-Titanium (NiTi). NiTi alloys used in Endodontics possess superelastic properties at body temperature (37C) that bring many advantages on the overall performance of the root-canal treatment. They can follow curved root canals more easily than stainless steel instruments and have been reported to be more effective in the removal of the inflamed pulp tissue and protection of the tooth structure. However, these instruments eventually fracture under cyclic bending loading due to fatigue, without any visible signals of degradation to the practitioner. This problem brought new challenges on how new instruments should be tested, as NiTi alloys are highly non-linear and present a large hysteresis cycle in the Elastic domain. Current existing standards are only available for Stainless Steel testing. Thus, many authors have attempted to design systems that can test NiTi endodontic files under fatigue loads. However, no approach has been universally adopted by the community yet, as in most cases they are based on empirical set ups. Following a more systematic approach, this work presents the results of rotary fatigue tests for several NiTi wires from different manufacturers (MemryTM and EuroflexTM). The tests were done on a versatile fully automatic rotary bending testing machine. The formulation is also presented, where the material strength reduction can be quantified from the determination of the strain and the number of cycles until failure.

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Keywords: Fatigue; Files; NiTi wires, Life evaluation;

1. Introduction

In dentistry, the root canal procedure is done using a rotary file that removes the existing nerve endings on a tooth. In the past, endodontic files used in this procedure were made from highly flexible steel alloys. However, steel alloy files, while being flexible, are still too rigid to avoid damaging the walls of the root canals. In order to minimize these adverse effects, Nickel-Titanium alloys are now being used in the design of endodontic rotary files instead of stainless steel alloys. NiTi alloys are superelastic metal alloys that are able to fully recover from large deformations

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(up to strains of 10% [1]). These alloys, however, have a drawback when compared to steel files: their fatigue life is relatively shorter than steel and, as seen in commercial endondontic files, they break without a previous mechanical warning, increasing the risk of the file failing inside the teeth.

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 tests are the tests that most accurately replicate the kind of loads and deformation a file is subjected to when inside a root canal. The great majority of the existing machines in the literature only perform the fatigue test with a predetermined set of shapes. However, most of the imposed deformations are far from the complex shapes of the root canals. [2].

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 an advantage of being more versatile than the more common machines with simulated canal carved in a stainless steel plate, where one can have only one predetermined curvature per plate [4–7]

In this work, an automated configurable rotary bending-testing machine was designed. 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 in 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.

The machine design also enables rotary bending tests with constant curvature (constant strain) along a segment. With a constant strain, one can compare directly the result 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 metallic phase of the alloy during the test.

2. Designing the 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. In our machine, however, the pins are positioned at configurable locations using servomotors. Configurable positioning enables a greater precision and repeatability, while providing a simple interface (Fig. 1).

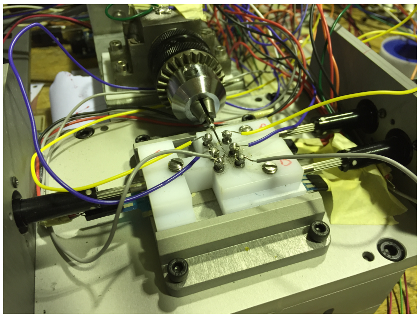

Fig. 1: Testing area with an endondontic file.

For the rotation of the specimens, a brushless DC motor with variable speed is used instead of the more common contra-angle. With a standalone DC motor, one can control the velocity of the test more precisely and automatically. The motor is able to do tests from 100rpm (16.67Hz) to 3000rpm (50Hz), which covers the range of most NiTi endodontic files with a drive speed usually between 150 and 350rpm.

To detect when the specimen fail (whether it is wire or an endondontic file), an electronic failure detection system was implemented. This system uses the natural conductivity of NiTi alloys to detect any failure by constantly monitoring the level of voltage between the specimen and each pin. When the circuit is open it means that the specimen failed and the test stops automatically.

3. Positioning control and Constant Curvature

The most important aspect of this machine is its ability to generate bending configurations automatically. The configurations are set by positioning the pins (Fig. 1) in order to deform the specimen into a shape (Fig.2). The

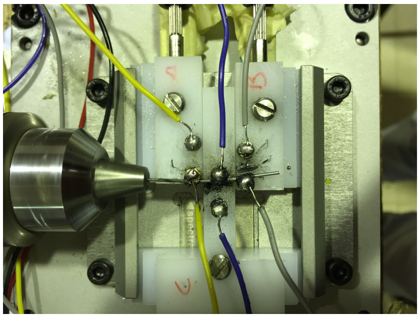

Fig. 2: Wire deformed during a test.

machine software enables two positioning modes: individual pin positioning and constant curvature radius generation.

3.1. Pin positioning

To position the pins the machine needs a linear motor and a positioning sensor to provide the feedback for the controller. The motors used are three Haydon kerk 21H4K linear stepper motors that have a step of 6μm and generate a maximum force of 30N. The positioning sensors are flexible linear potentiometers that are positioned under the pin trays. When the "wiper" moves along the potentiometer, it changes the voltage level of the potentiometer linearly, giving a direct reading of its position. Using the sensor readings, a digital feedback control loop is controlled by the associated microprocessor. The overall positioning precision is ≈ 10μm in all pins.

3.2. Beam Model for the Rotary Testing Machine Specimens

With the pin position control done, the machine is ready to make the tests. However, imposing a constant curvature in a setup with a clamped end (the handle of the specimen that is coupled with the rotation motor) is not trivial. In a common four-point bending test the pins are positioned in pairs and the outermost pair is fixed, leaving only one parameter to be set. In the rotary fatigue machine, all three pins are independent and the clamping must be compensated.

To calculate the correct pin positions that impose a constant curvature, one has to use beam theory. Using the Euler-Bernoulli beam theory, one has the relation in (1) for a uniform beam.

$$EI\frac{\mathrm{d}^4 w}{\mathrm{d}x^4} = q(x) \tag{1}$$

where, q is the distributed transverse load, E is the Young Modulus, I is the second moment of area of the cross-section, x is the dimension across the length of the beam and w is the beam deflection.

Since there are no distributed transverse loads (only point loads), equation (1) reduces to:

$$\frac{\mathrm{d}^4 w}{\mathrm{d}x^4} = 0 \tag{2}$$

Solving (2) one obtains a complete fourth-order polynomial.

$$w(x) = \frac{1}{6}c_1 x^3 + \frac{1}{2}c_2 x^2 + c_3 x + c_4 \tag{3}$$

where the coefficients c_1, c_2, c_3 and c_4 are to be determined using the boundary conditions.

For the particular case of this device, the specimen must be subdivided into four sub problems as shown in Fig. 3. Each section in Fig. 3 has its own set of coefficients for (3).

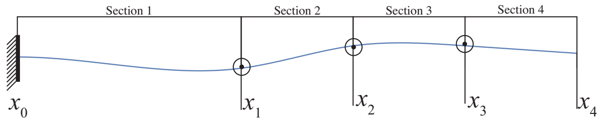

Fig. 3: Beam model of the specimen, where x_0 is the clamped end of the specimen; x_1, x_2 and x_3 are the positioning pins; and x_4 is the free end of the specimen.

3.3. Constant Curvature Generation for Wire Specimens

The main advantage of having a constant curvature in a uniform beam is that in that region the strain is also constant and proportional to the radius as in (4).

$$\epsilon_x = -z\frac{1}{\rho} \tag{4}$$

where ρ is the radius of curvature, ϵ_x is the strain along the length of the beam and z is the distance to the neutral surface.

For an infinitesimal element (4) becomes:

$$\epsilon_x(x) = -z\frac{\mathrm{d}^2 w}{\mathrm{d}x^2} \tag{5}$$

which can be applied to (3) resulting the strain profile of the specimen along its length.

However, we want a constant strain level for an entire segment of the specimen and, consequently, the position of the pins must be determined in to generate a constant strain section.

Imposing the following condition:

$$\epsilon_x(x_1) = \epsilon_x(x_2) = \epsilon_d \tag{6}$$

where $\epsilon_x(x)$ results from applying (5) into (3) and ϵ_d is the desired strain, we will have a constant strain level in the second section of the specimen (Fig. 3).

From (6), two displacement values can be extracted[1], which means that an extra constraint must be supplied. Since no other equation obtained from the Euler-Bernoulli model gives extra usable information, the last displacement (W_1) must be obtained by indirect means.

The parameter W_1 gives the amount of deflection imposed to the specimen in the first section, just after the clamp. Since we can obtain a W_2 and W_3 that results in a constant strain level for any W_1, the overall deflection of the specimen can be controlled by this parameter. The cost function for the optimization is a standard square minimum:

$$C(W_1, W_2, W_3) = W_1^2 + W_2^2 + W_3^2 \tag{7}$$

where C is the cost function value, W_1 is the optimization variable and W_2 and W_3 are already known. The resulting cost function is algebraic in respect to W_1 and the minimum can be calculated directly.

With all the positions, we can change the shape of the neutral surface (points x_1, x_2 and x_3 in Fig. 3) to obtain the constant strain. However, the wire and the endodontic files have finite thickness and, consequently, the actual positions of the pins must be adjusted accordingly.

The position of the pins must take into account the influence of thickness in the position and the requirement that the wire must be tangent to the pins at all times. This leads to a variable distance between the contact point at the surface and the neutral surface. This is done in two steps: first we find an offset of the neutral surface that passes by the center of the pins (the pins have a diameter of 2mm at the contact point), then the following equation must be solved:

$$(r + 1)\sin(\arctan(w'(t))) + t = x_{pin} \tag{8}$$

where r if the radius of the wire, w' is the first derivative of the beam deflection, t is a parameter that follows the wire length (at the neutral surface and considering that there is no axial deformation $t \approx x$) and x_{pins} is the position of the pin (measured from the clamping point).

[1] Only two parameters could be obtained analytically, because the system in (6) only has two equations

The resulting t form (8) when replaced on the offset curve gives the position of the pin (Fig.4). Equation (8) has to be solved numerically and each time a new deformation is calculated.

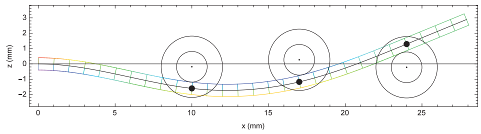

Fig. 4: Beam under a desired constant strain of 2%, with color-coded strain and tangent pins.

For the case of Fig. 2, which corresponds to setting the desired strain to 2%, the curvature can be seen in Fig. 5. Knowing that the internal radius of the pins is 1mm and using (4), we obtain that the angle of the arc is $\approx$ 11.71 deg

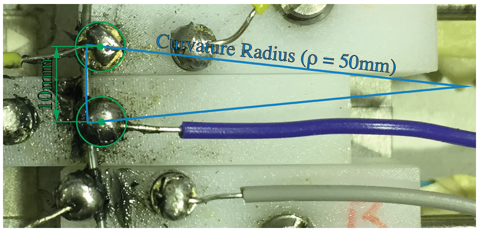

Fig. 5: Deformed wired with a desired strain of 2% superimposed with the curvature radius.

and the radius of curvature is 50mm. These two parameters can be used to compare results with testing methods such as the Pruet et al [8].

4. Results for a NiTi Wire

The first materials to be tested in the rotary fatigue machine were a Memry™ and a Euroflex™ wires, both with a diameter of 0.8mm. The wires, when under an uniaxial load, has the stress-strain relation in Fig. 6.

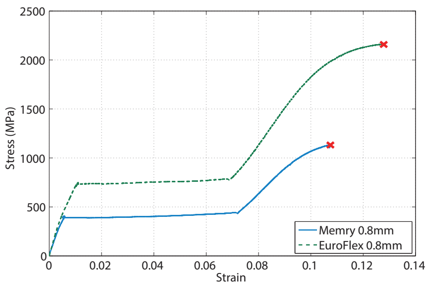

Fig. 6: Uniaxial tension test of the Memry™ 0.8mm diameter wire.

Figure 6 has three distinct regions: a first austenitic elastic region, a horizontal elastic region with a mixture of austenitic and martensitic phases (also known as R-phase) and a final plastic martensitic region. Another characteristic of these Ni-Ti alloys is that they exhibit a large hysteresis when unloading occurs. For simplicity sake, this phenomenon was not considered in the study of the fatigue of the wire specimens.

The fatigue tests were concentrated on the first two regions, imposing strains level from 0.8% to 6%. The results can be seen in Fig. 7. The specimens with strains smaller or equal to 1% (corresponding to the first zone in the stress-strain plot in Fig. 6) show a large fatigue life when compared with the rest of the points, with two specimens never failing. 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 cycle for the Euroflex™ wires.

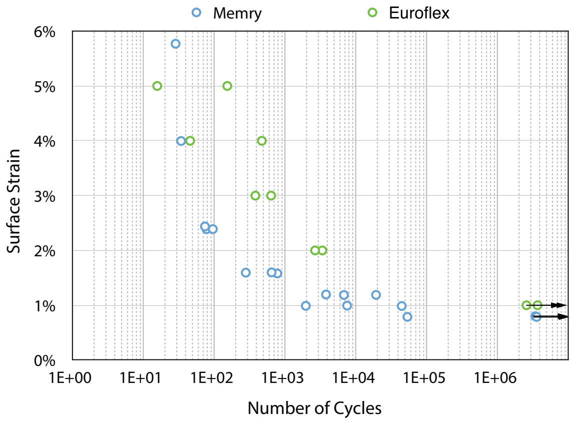

Fig. 7: Strain vs. number of cycles for a Memry™ 0.8mm diameter wire.

5. CONCLUSIONS

The work presented on this paper presents a testing apparatus designed to perform rotary fatigue tests on NiTi endondontic files and wires. The testing machine was designed to be versatile, enabling a series of testing configurations and test types, using computer controlled automatic positioning of system that bends the specimens into user supplied shapes or into a bending configuration that has a constant strain section. A series of fatigue tests were done using a Memry™ and Euroflex™ 0.8mm diameter wires. The wires showed a very long fatigue life (most of the specimens did not fail) when under strain levels in the elastic austenitic phase. When imposing strain in the R-phase 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).

For future work, other wires with different diameters will be tested, as well different endondontic files.

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