# Effects of a lubricating aqueous gel on the operative life of Ni-Ti endodontic rotary instruments: preliminary investigation

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**ABSTRACT.** The use of Ni-Ti alloys in the practice of endodontic comes from their important properties such as: shape memory and superelasticity phenomena, good corrosion resistance and high compatibility with biological tissues. In the last twenty years a great variety of nickel-titanium rotary instruments, with various sections and taper, have been developed and marketed. Although they have many advantages and despite their increasing popularity, a major concern with the use of Ni-Ti rotary instruments is the possibility of unexpected failure in use due to several reasons: cyclic fatigue, novice operator handling, presence manufacturing defects, etc. Recently the use of an aqueous gel during experimental tests shown a longer duration of the instruments.
The aim of the present work is to contribute to the study of the fracture behavior of these endodontic rotary instruments particularly assessing whether the use of the aqueous lubricant gel can extend the their operative life stating its reasons. A finite element model (FE) has been developed to support the experimental results. The results were quite contradictory, also because the Perspex (Poly-methyl methacrylate, PMMA) cannot simulate completely the dentin mechanical behavior; however the results highlight some interesting points which are discussed in the paper.

**SOMMARIO.** L'uso di leghe Ni-Ti negli strumenti endodontici deriva dal fatto che queste presentano importanti proprietà come: la memoria di forma e la superplasticità, buona resistenza alla corrosione e alta compatibilità con i tessuti biologici. Gli strumenti rotanti in nichel-titanio, con varie sezioni e conicità, sono stati sviluppati e commercializzati nell'ultimo ventennio. Pur possedendo innumerevoli vantaggi, gli strumenti in Ni-Ti, tendono ad andare incontro ad una prematura rottura dovuta a diversi fattori. In particolare alla fatica ciclica, a improvvise sovrasollecitazioni indotte da una non buona manualità dell'operatore, a presenza di difetti generati in fase di fabbricazione ecc. Recentemente durante la pratica clinica sugli strumenti sono stati provati diversi tipi di gel al fine di prolungarne la vita operativa. Con questo lavoro si è cercato di dare un contributo allo studio del comportamento a frattura di questi strumenti, in particolare valutando se il gel (acquoso) abbia contribuito efficacemente alla maggior durata degli strumenti e su quali basi. Sono stati effettuati test di fatica e meccanici utilizzando simulacri di Perspex (Poly-methyl methacrylate, PMMA) in sostituzione della dentina. I risultati abbastanza contraddittori, anche per il fatto che il Perspex non può simulare perfettamente la dentina, in ogni caso evidenziano alcuni punti interessanti che vengono discussi nel presente lavoro. Inoltre, a supporto delle indagini sperimentali, è stato sviluppato un modello agli elementi finiti (FEM), che ha permesso di confermare i risultati.

**KEYWORDS.** Endodontic rotary instruments; NiTi Alloy; Aqueous gel lubricant.

## INTRODUCTION

In the practice of endodontics the introduction of Ni-Ti rotary instruments has reformed root canal treatment by reducing time required to finish the preparation and minimizing procedural errors associated with stainless steel hand instrumentation. The use of Ni-Ti alloys for that applications comes from their important properties such as: shape memory and superelasticity phenomena, good corrosion resistance and high compatibility with biological tissues. Particularly superelasticity may allow Ni-Ti files to be placed in curved canals, such as that of molars, with less lateral force than that employed with stainless steel instruments.

Despite their increasing popularity, a major concern with the use of Ni-Ti rotary instruments is the possibility of unexpected failure in use (1,2). The breaking mode of Ni-Ti rotary instruments may be classified into flexural fatigue and torsional (shear) fracture according to their appearance after breaking (3). Torsional failure is usually accompanied with macroscopic distortion or unwinding of the flutes adjacent to the fractured end, whereas flexural fatigue often presents as an unexpected fracture with no unwinding defects. All manufacturers stated that the only predictable way to prevent flexural fatigue is to discard the instrument regularly after a certain number of uses. The cycle number for instrument re-using depends on the type of tooth that was treated, with the greatest number in anterior teeth and the lowest in molars (4).

It is usually assumed that lubrication during root canal preparation would lower mechanical stress on rotary root canal instruments and therefore prevent instrument failure (5). However, few data occur in the literature to confirm or refute that opinion. A lubricant may play a physical effect by moving debris away from the rotating instrument. Furthermore, chemical additives could operate on the root canal dentin to facilitate instrumentation, as example Calcium-chelating lubricant, by dissolving inorganic dentin components, soften the root canal wall, whereas sodium hypochlorite (NaOCl) attacks the organic dentin matrix (6). Thus, both NaOCl and chelators can lower root dentin microhardness (7). The impact of lubricant parameters on simulated root canal instrumentation was investigated and the performed tests allow to demonstrate that an aqueous lubricant was more beneficial than a gel-type counterpart (8).

The potential difficulty in removing instrument fragments from root canal and a perceived adverse prognostic effect of this procedural complication, together with short time duration of that rotary instruments are the main reason to study the instrument fracture mechanism and how it may be prevented rather than treated. The objective of this study is to determine the incidence and mode of instrument failure of Ni-Ti rotary systems with and without aqueous lubricant. A preliminary FEM analysis has been performed on the rotary instruments in order to verify the applied stress.

## MATERIALS AND TECHNIQUE

This study has been carried out on two different Ni-Ti rotary instruments manufactured by MICRO-MEGA® and named HERO 642®. The two instruments ,shown in Fig. 1 (red, the bigger, and yellow, the smaller), present as main difference the root cross sectional diameter, the yellow instrument has 0.75 mm in diameter while the red has 1.0 mm in diameter. Both kind of instruments has been observed with a Scanning Electron Microscope (SEM HITACY S-2500, KEVEX EDS microprobe). DSC analysis has been carried out in order to identify eventual phase transition of the Ni-Ti material.

In order to test this instruments, root canal treatments have been simulated employing the Perspex simulator shown in fig 2. Test has been carried out with an equipment for root canal treatment manufactured by NSH (ENDO-MATE DT) with the following standard settings: rotation speed 140 rpm, torque 3.0 N·cm. Test has been carried out at room temperature with or without the use of an aqueous lubricant gel which composition is object of a patent request.

The test procedure considers the repetition of 30 second cycles. After each cycle the instruments is removed from the Perspex simulator and cleaned in order to remove the plastic debris and to identify eventual macroscopic defects. Every four cycles the simulator is replaced because the canal is enlarged by the mechanical processing thus it doesn't offer any

more resistance. It has been observed that during the first cycle the rotary instrument reaches only the half of the canal, during the second cycle it reaches the bottom of the canal, during the other 2 cycles the instrument works only to enlarge the canal.
The insertion of rotary instrument must be as parallel as possible to the canal entrance and the operator have to be particularly accurate inserting and maintaining the tool in the root canal, with regular *up and down* movement, necessary in order to avoid the seizing of the instruments inside the simulator .
Cycles have been repeated up to the instrument break or up to macroscopic defects appearance.

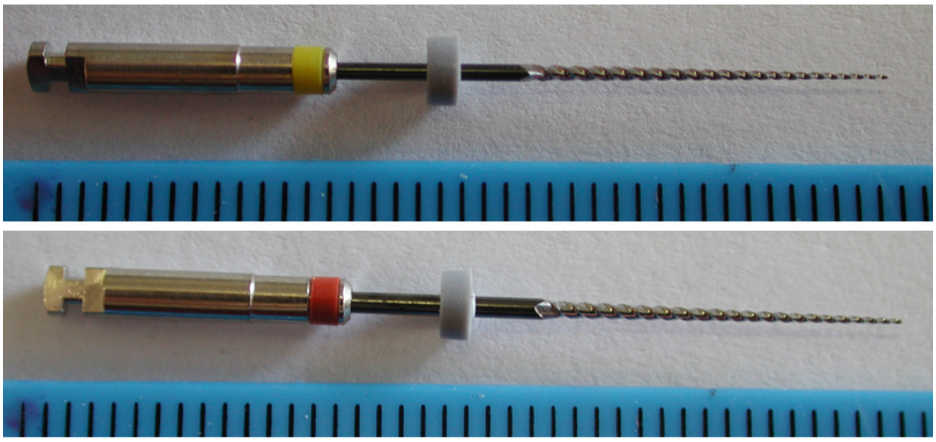

Figure 1: MICRO-MEGA HERO642 rotary instruments studied.

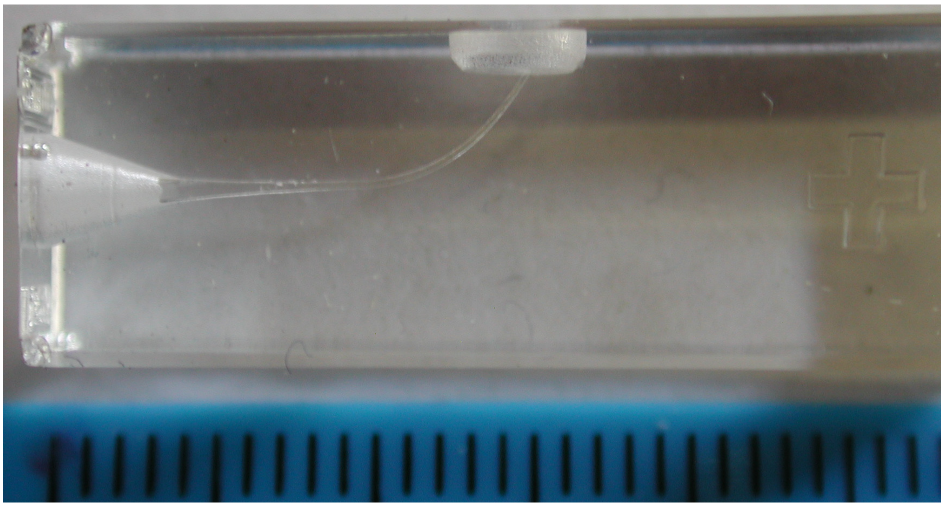

Figure 2: ENDO-TRAINING-BLOC employed as simulator.

Periodically the rotary instruments have been cleaned with Isopropylich alcohol and ultrasounds and then observed with SEM in order to evaluate presence of surface defects. After the instrument break, the fracture surfaces have been characterized by SEM.
During the second cycle, when the rotary instruments reaches the bottom of the simulator canal, sometimes the rotation has been interrupted and the simulator-rotary instruments system has been subjected to a traction test in order to evaluate the load required to extract the instruments from the Perspex simulator. That test have been carried out employing an Instrom 3367 tensile machine. Tensile test have been carried out with a crosshead speed of 1mm/min. A load vs. displacements curves have been obtained.
To go further in the study of the Ni-Ti instruments, the present investigation considers the mechanical behavior under torsion and extension. Therefore a FEM Static analysis was carried out by applying an axial moment (3 N·cm), and an axial load (50 N) in order to test the structural status of endodontic Ni-Ti rotary instruments, using a representative loadings.

This analysis does not take into account the forces applied to two models by any external structure like dentin or Perspex simulator.
An accurate three-dimensional solid model of Ni-Ti rotary file was created by reconstructing its 3D geometric shape using a computer aided design software (CATIA, Dassault Systeme). Then finite element (FE) model of the instrument was obtained by meshing the pre-established solid model. The geometric models are made by rotating the characteristic cross section, shown in Fig. 3, through 360 degrees over the whole length.
Even if the performed tests don't allow us to confirm, in literature is reported that continuous unidirectional rotation causes development of complex stresses in nickel titanium rotary instruments. The finite element analysis is aimed to study and compare stress distribution and behavior of two rotary instruments, of same shape, same taper but different root cross section diameter, see Fig. 3. Both instruments were tested under equal loads.
The models are divided into discrete tetrahedral elements (a ten-nodes iso-parametric solid element). The total numbers of elements are 863972 (for 1302293 nodes) for the bigger file and 139863 (for 217475 nodes) for the smaller one.

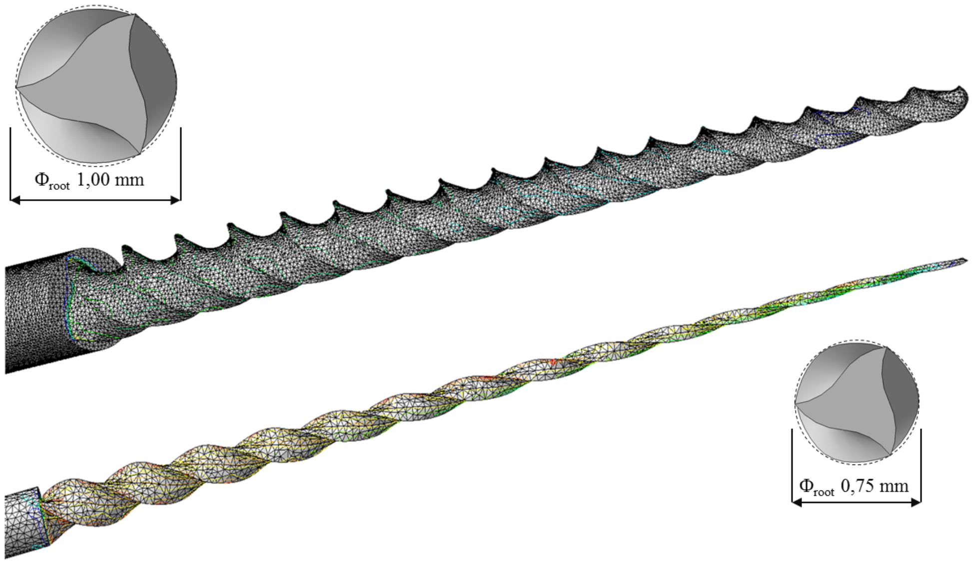


Figure 3: Detail of the root cross section of the 3D model and the tetrahedral meshes

Material properties of the instruments like Young's Modulus, Poisson's Ratio and elastic limit were incorporated, the main mechanical properties are resumed in Tab. 1. The surrounding conditions, force and moments were fixed. In both cases, the model was blocked at one end and was loaded with a concentrated torsional or bending all along the file.

| | |
|---|---|
| Elastic Modulus | 80 GPa |
| Density | 6450 kg/m$^3$ |
| Poisson ratio | 0.34 |
| Yeld Strength | 560 MPa |
| Coeff. Of linear thermal expansion | 9.5 $10^{-6}$/K |

Table 1: Ni-Ti Alloy main Mechanical properties.

## INSTRUMENTS CHARACTERIZATION

The EDS analysis of the HERO 642 instruments give the following results: Ni 54,9$\%_w$ (49.9 $\%_a$) , Ti 45,32$\%_w$ (50.1$\%_a$) as a Ni-Ti superelastic alloy (NiTiNol). The SEM observations of the instruments - as received from the manufacturer - show that the surfaces of all instruments are covered for the entire length by parallel signs (quite perpendicular to the file, Fig. 4) and by an high quantity of micro-cavities (Fig. 5).

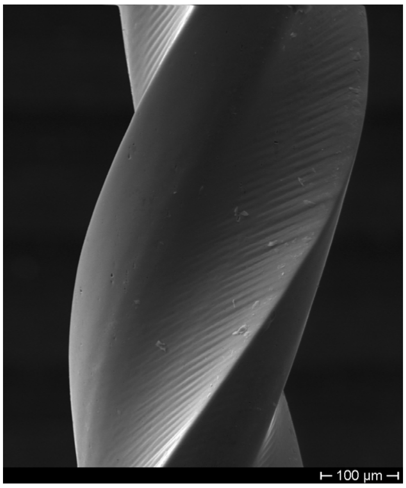


Figure 4: SEM micrograph of as received instruments surfaces

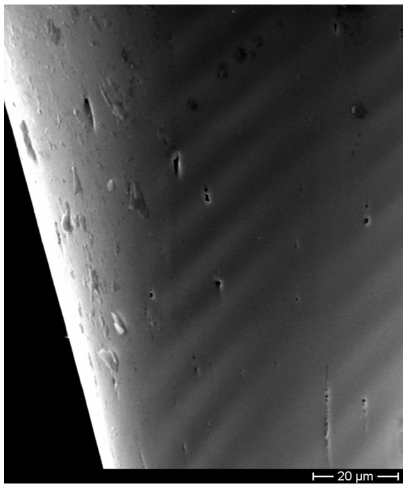


Figure 5: SEM micrograph of as received instruments surfaces

## YELLOW INSTRUMENT TEST RESULTS

Tab. 2 reports the results of the test performed on the yellow instruments. Fig. 6 and 7 show the load vs. displacements curves of the extraction test carried out with and without the lubricant use.

Instruments tested without lubricant gel fail in two different way. Instrument number 13 shows a macroscopic unwinding (Fig. 8 and 9). It can be observed that unwinding is clearly visible already before the extraction test. This kind of damage is probably caused by rotation of instruments inside the canal and not by tensile load applied during the extraction phase. The instrument number 16 instead suddenly break approximately at the tip without showing any macroscopic failure sign before the last test cycle. The instruments tested with lubricant gel have shown this last kind of failure, observed by SEM.

| Instrument n° | Lubricant gel | Break/ damage revolutions | Break/ damage cycles | Simulators employed | Damage type |
|---|---|---|---|---|---|
| 13 | No | 350 | 5 | 2 | Unwinding at the 9 revolution |
| 14 | Yes | 2065 | 30 | 8 | Break at the revolution 4 |
| 15 | Yes | 1545 | 23 | 6 | Break at the revolution 4 |
| 16 | No | 1820 | 27 | 7 | Break at the revolution 4 |

Table 2: Yellow instrument test results.

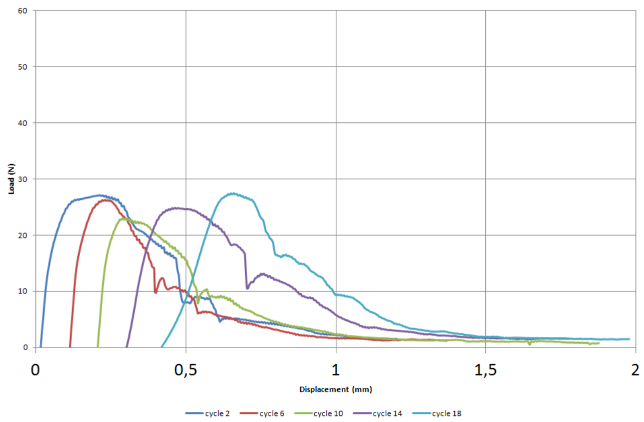


Figure 6: Load vs displacements plot of the extraction test carried out with gel lubricant

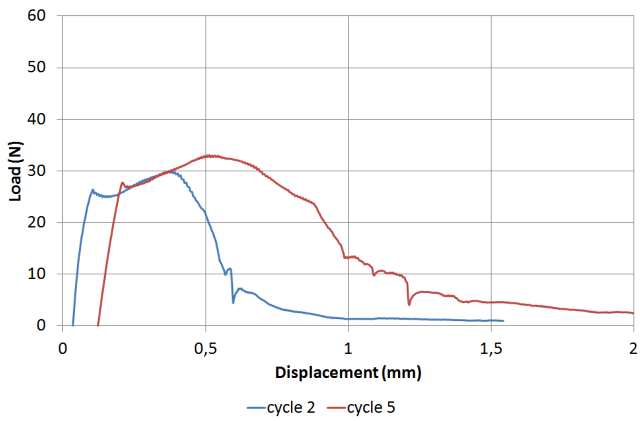


Figure 7: Load vs displacements plot of the extraction test carried out without gel lubricant

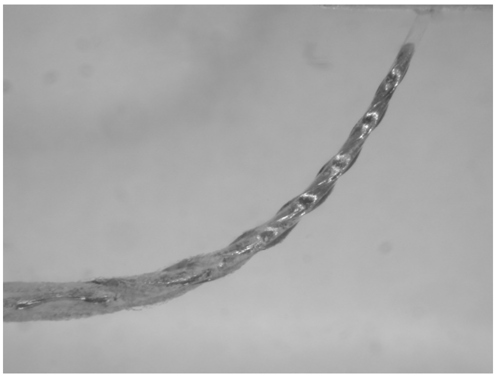

Figure 8: Instrument 13 inserted into the simulator.

Figure 9: Instrument 13 after the extraction test.

The microcavities observed on the instrument surfaces evolve since the early test cycles producing microcracks (Fig.10). Often this microcracks joint together producing cracks usually in the axial direction. However the failure happens only when this kind of defect growths on the file or in its proximity (Fig. 11). In this point the stress concentration is particularly high. The fracture surface analysis shows a wide net of dimples highlighting a plastic behaviour of the fracture process (Fig. 12). No sign of fatigue has been observed.

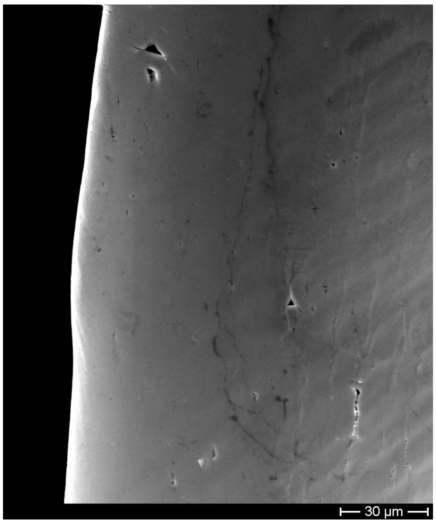


Figure 10: SEM micrographs of instrument number 16.

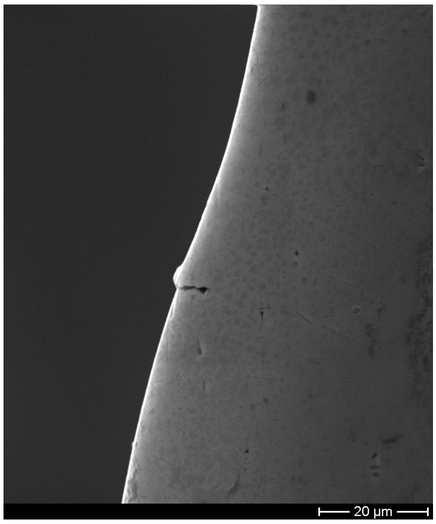


Figure 11: SEM micrographs of instrument number 15.

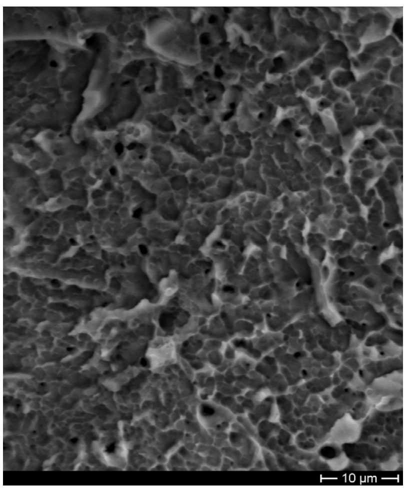


Figure 12: Fracture surface of instrument number 15.

The study of the load vs. displacements curves allows to point out the effect of the lubricant gel. During the extraction test carried out without the use of gel the load rise linearly up to a value of about 27 N. At this point the tool is free and a momentary load drop can be observed. Then the load rise again, but more slowly than before, and with a typical serrated curve up to the maximum load (approximately 32 N). This last load rise is due to the friction between the canal surface and the instrument. Instead during extraction test carried out with gel the load drop, which happens at the detachment between instrument and canal, is never observed. Moreover the detachment load (approximately 24 N), the gap between detachment load and maximum load (approximately 26 N) and the displacement necessary to reach the maximum load are lower than that without lubricant.

## RED INSTRUMENT TEST RESULTS

Tab. 3 reports the results of the test performed on the yellow instruments. Fig. 13 and 14 show the load vs. displacements curves of the extraction test carried out with and without the lubricant use.
The behaviour of the larger instruments is similar to those observed for the yellow instruments. Particularly, the failure mechanism for the red instruments working without lubricant is the unwinding (Fig. 15). It can be observed the formation of:

- several microcracks on the instrument surface (Fig. 16)
- deep cracks on the instrument file (Fig. 17).

Instead, for test performed with lubricant, the instrument fails suddenly without any macroscopic previous sign. On the surface and on the file of the instruments appear the usual microcrack (Fig. 18 and 19).
Also in this case the fracture surface are characterized by a dimples network without the presence of any fatigue sign (Fig. 20).
Concerning the load vs. displacements extraction curves, the consideration taken for the yellow instruments can be extended to the red one. The differences observed concern both the detachment load and the maximum load, which in this case are quite higher.

| Instrument n° | Lubricant gel | Break/ damage revolutions | Break/ damage cycles | Simulators employed | Damage type |
|---|---|---|---|---|---|
| 7 | Yes | 1820 | 26 | 7 | Break at the revolution 4 |
| 8 | No | 350 | 5 | 2 | Unwinding at the revolution 2-4 |
| 9 | No | 840 | 12 | 3 | Unwinding at the revolution 2-4 (cycle 6), Break at revolution 3 |
| 10 | Yes | 1120 | 16 | 4 | Break at revolution 2 |
| 11 | No | 1260 | 19 | 5 | Unwinding at revolution 7-9 |
| 12 | No | 980 | 14 | 4 | Unwinding at revolution 8-10 |

Table 3: Red instrument test results.

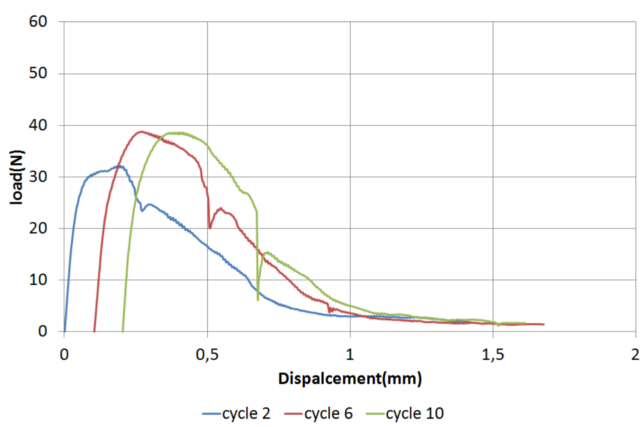


Figure 13: Load vs displacements plot of the extraction test carried out with gel lubricant.

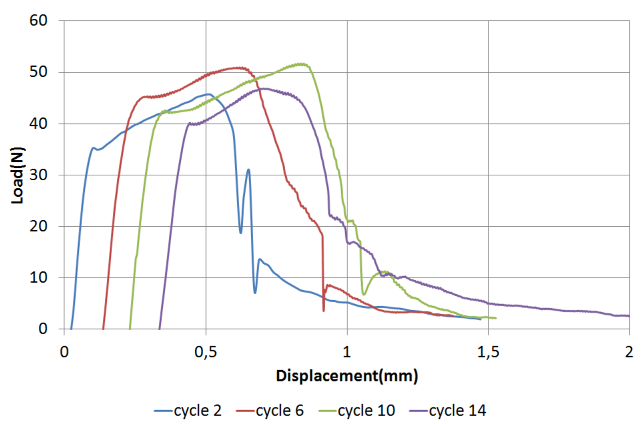


Figure 14: Load vs displacements plot of the extraction test carried out without gel lubricant.

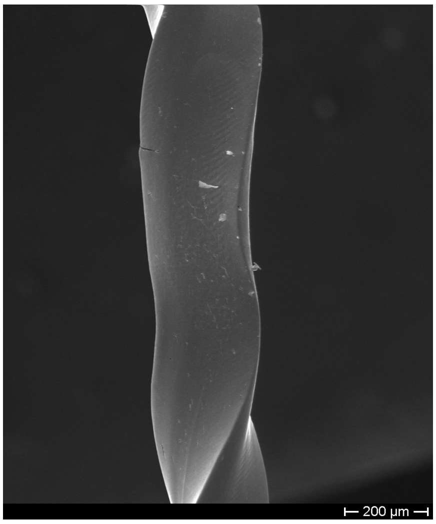

Figure 15: SEM micrographs of instrument number 9.

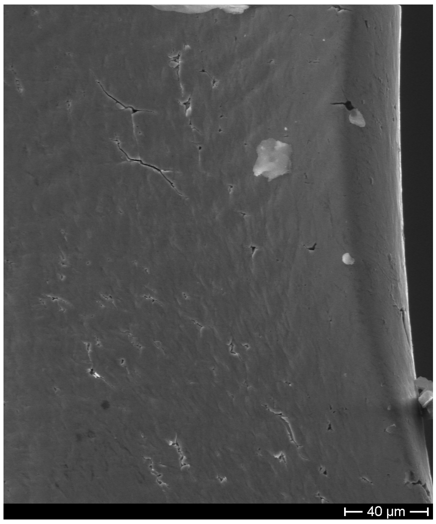

Figure 16: SEM micrographs of instrument number 9.

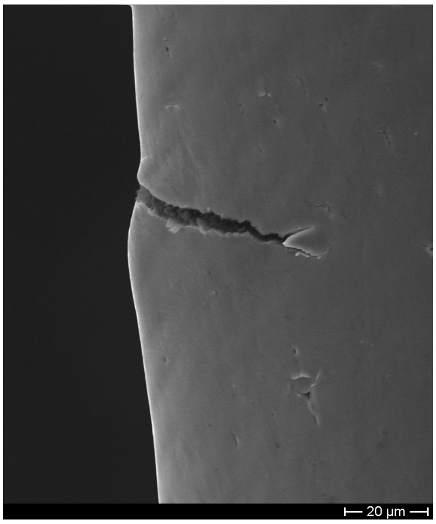

Figure 17: SEM micrographs of instrument number 9.

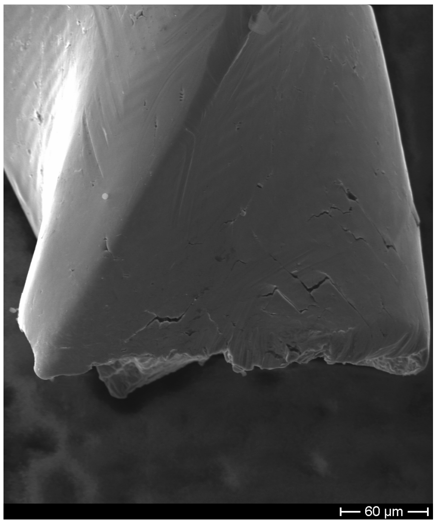

Figure 18: SEM micrographs of instrument number 7.

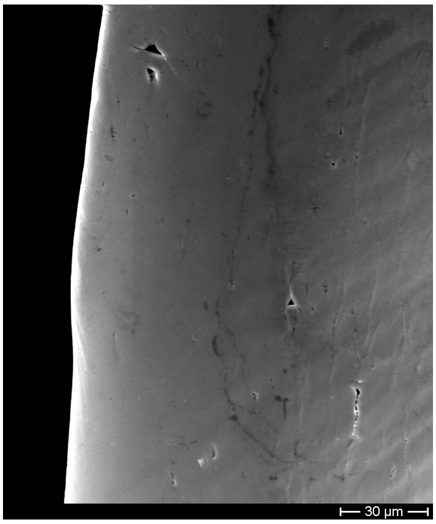

Figure 19: SEM micrographs of instrument number 7.

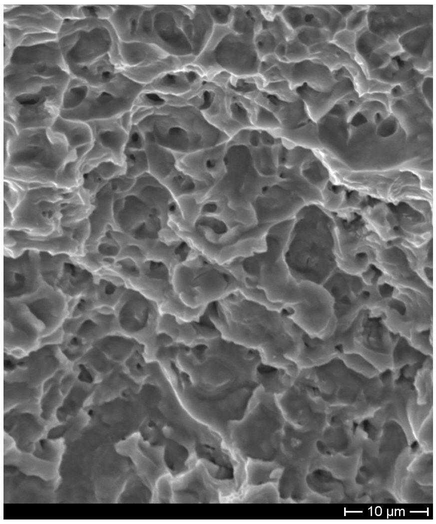

Figure 20: Fracture surface of instrument number 7.

## DSC ANALYSIS

The Ni-Ti alloys can show both superelastic behaviour or shape memory effects. It depends from the manufacturing process. The materials employed for the realization of rotary instruments must show a superelastic behaviour. In order to verify if, in operation, an eventual phase transition, which could modify the Ni-Ti alloy properties, happens a DSC analysis in the range of temperature 25-90 °C has been performed. The Fig. 21 reports the DSC plot obtained. As it can be seen the plot is quite linear highlighting the absence of any phase transition.

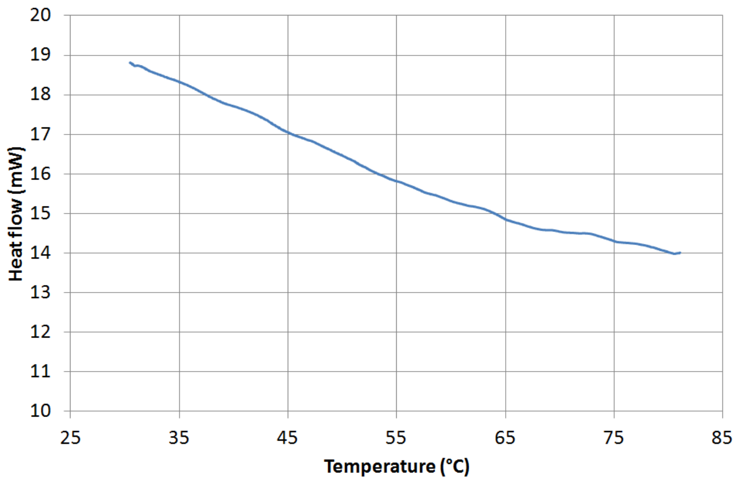


Figure 21: DSC Plot.

## PRELIMINARY FEM ANALYSIS

On first approximation the distribution of the coupled torsional and extensional stresses depends primarily on the root cross sectional diameter. The model also shows that under torsion, the maximal stress is localized at the root of the instrument. Fig. 22 highlights the distribution of Von Mises stresses in the static test. The smaller instrument, tested under the same load, goes in the plastic region particularly on the root, where the stress concentration acts both on the cutting edge and on the body; then concentrating only on the body, along the whole length, leaving undamaged the tip.

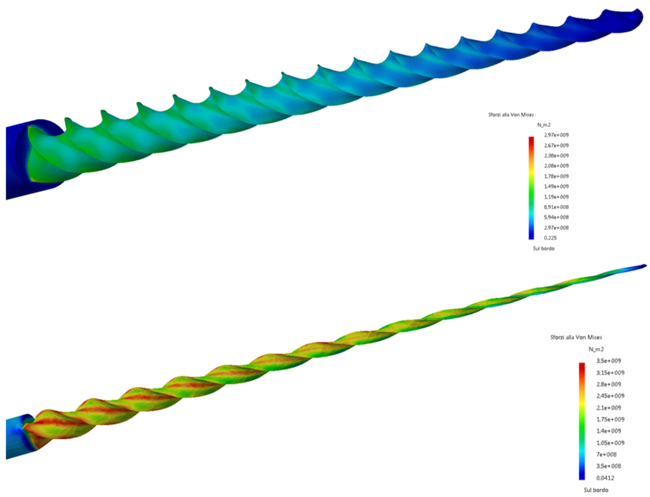

Figure 22: Von Mises Sterss Distributions

In conclusion, within the limitations of the present study, the use of a 3-D finite elements approach, in order to carry out studies about the geometry of commercially available Ni-Ti instruments and their mechanical properties, appears to be relevant.

## CONCLUSIONS

Experimental tests, performed on two different geometry of Ni-Ti alloy rotary instruments, highlight that the failure mechanisms are principally two:

- the unwinding in correspondence of the highest curvature of the line;
- a sudden break of the apex related to the cracks development on the cutting edge; these cracks are generated from the defects present at the origin (i.e. surface microcavities).

The tests carried out on the Perspex simulator revealed no evident effects due to cyclic fatigue.

The fatigue test showed a tendency to an increase of the operating life of the instruments when used with aqueous lubricant gel. This effect is related to a better capacity to remove and extract the debris from the root canal and especially by the reduction of loads required during the extraction phase. The tests performed on the Perspex simulator have some limitations related to the material characteristics, which does not represent properly the mechanical properties of the dentin and the manual dexterity of the operator, whose experience plays a key role.

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