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Low-cycle fatigue of NiTi rotary instruments of various cross-sectional shapes

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Abstract

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Aim To compare the low-cycle fatigue (LCF) behaviour of some commercial NiTi instruments subjected to rotational bending, a deformation mode similar to an engine-file rotating in a curved root canal, using a strain-life analysis, in water.

Methodology A total of 286 NiTi rotary instruments from four manufacturers were constrained into a curvature by three rigid, stainless steel pins whilst rotating at a rate of 250 rpm in deionized water until broken. The number of revolutions was recorded using an optical counter and an electronic break-detection circuit. The surface strain amplitude, calculated from the curvature (from a photograph) and diameter of the fracture cross-section (from a scanning electron micrograph), was plotted against the number of cycles to fracture for each instrument. A regression line was fitted to the LCF lives for each brand; the value was compared with that of others using one-way analysis of variance (ANOVA). The number of crack origins observed on the fractographic view was examined with chi-square for differences amongst various groups.

Results A linear strain-life relationship, on logarithmic scales, was obtained for the LCF region with an apparent fatigue-ductility exponent ranging from −0.40 to −0.56. The number of crack-initiation sites, as observed on the fracture cross-section, differed between brands (χ^2, $P < 0.05$), but not LCF life (one-way ANOVA, $P > 0.05$).

Conclusions The LCF life of NiTi instruments declines with an inverse power function dependence on surface strain amplitude, but is not affected by the cross-sectional shape of the instrument.

Keywords: breakage, fracture, nickel-titanium, root canal preparation, strain-life analysis.

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Endodontic treatment has benefited from the introduction of NiTi rotary root canal instruments. However, clinicians remain concerned about their breakage in use, although the actual prevalence of such breakages has been indicated to be low (about 5%) (Parashos & Messer 2004). NiTi rotary instruments may fracture as a result of shear or fatigue failure, with the latter being implicated in more than one-third of those instruments fractured clinically (Sattapan *et al.* 2000, Parashos *et al.* 2004, Peng *et al.* 2005, Shen *et al.* 2006). Although previous studies have shown that the fatigue life of various NiTi instruments is affected by the radius of curvature (Pruett *et al.* 1997, Mize *et al.* 1998, Haïkel *et al.* 1999) and the instrument size (Yared *et al.* 1999, Gambarini 2001, Peters & Barbakow 2002), none has examined the strain imposed on the instrument (which is related to these two variables) during the test and hence a relationship between them and fatigue life has not been determined. One recent study has attempted to calculate the strain from the nominal dimension of the instrument (Bahia & Buono

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2005), but the author did not concern deviations of the actual product from specifications or manufacturing tolerance and the results must be treated with caution.

Increasing numbers of NiTi rotary instruments of various designs are now marketed. The instrument design can affect the magnitudes of stress and strain when it is subject to torsion or bending (Berutti *et al.* 2003, Xu *et al.* 2006). This, in turn, can influence the fatigue behaviour because the instrument design, and cross-sectional shape in particular, can predispose fatigue-crack initiation due to stress concentration. To date, there has been no report on how NiTi instruments of various cross-sectional shapes behave when subjected to rotational-bending, a deformation mode that resembles their use in curved root canals. The aim of this study, therefore, was to compare the low-cycle fatigue (LCF) behaviour of some commercially-available NiTi rotary instruments. The null hypothesis was that instruments of different cross-sectional shapes rotating with similar curvature have a comparable fatigue life.

Materials and methods

A machine was custom-made for performing a rotational-bending fatigue test for NiTi engine-files at various curvatures. Briefly, each NiTi instrument was constrained to a curvature by three rigid, stainless steel pins (horizontal position being adjustable); a digital photograph was taken of the curvature. The instrument was then allowed to rotate at 250 rpm until fracture (or until the test was abandoned). All broken fragments were measured for length and then examined under scanning electron micrograph (SEM); photomicrographs were taken of the fracture surface at various magnifications. For each instrument the radius of curvature R_c at the corresponding site of fracture was determined on the photograph, and the diameter of the fracture cross-section d on the photomicrograph using computer software (ImageJ 1.34n; NIH, Bethesda, MD, USA); this information allowed the calculation of the maximum surface strain amplitude ε_a at break for each instrument:

$$\varepsilon_a = \frac{d}{2R_c} \tag{1}$$

Four brands of regularly tapered NiTi engine-files (Table 1), each with a different cross-sectional form (Fig. 1), were tested at various curvatures under deionized water at 23 ± 2 °C. The number of revolutions or cycles to failure N_f was recorded electronically using an optical counter and a break-detection circuit.

Table 1 Four brands of NiTi instrument tested

Group	Brand name (manufacturer)	Cross-sectional shape	Batch numbers	No. tested	
				With N_f < 4000	Total
PF	ProFile (Dentsply Maillefer, Ballaigues, Switzerland)	Three U-shaped flutes and 'radial lands'	3701510, 5154060	87	106
K3	K3 (SybronEndo, Orange, CA, USA)	Asymmetrical and irregular with three sharp cutting edges	04C86C, 04H21H	63	74
HE	HERO Shaper (Micro-Mega, Besançon, France)	Resemble an S-file but with three sharp cutting edges	031804, 040204	40	51
FM	FlexMaster (VDW, Munich, Germany)	Triangular with convex sides	0505310334	50	55

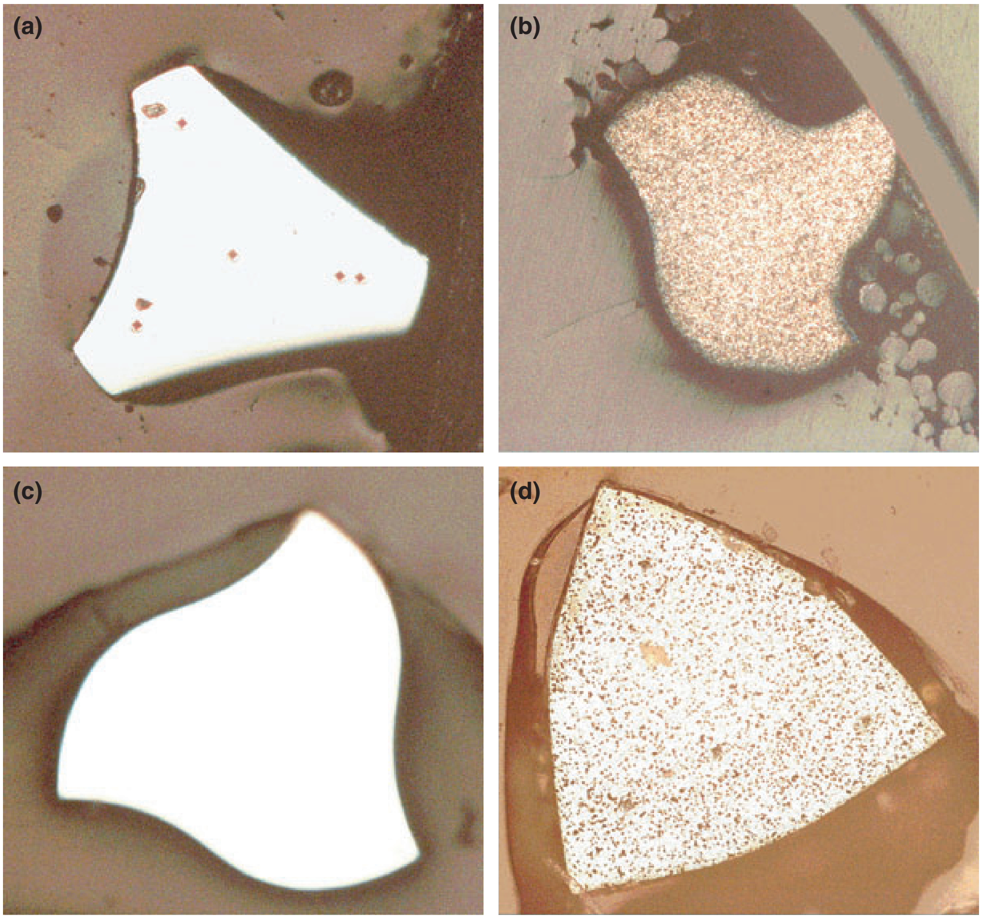

Figure 1 Cross-sectional shape (at about 5 mm from the tip and polished) of four brands of instrument: (a) ProFile (Dentsply Maillefer, Ballaigues, Switzerland); (b) K3 (SybronEndo, Orange, CA, USA) (Note: strip on the right of field is a positioning holder); (c) HERO Shaper (Micro-Mega, Besançon, France); (d) FlexMaster (VDW, Munich, Germany).

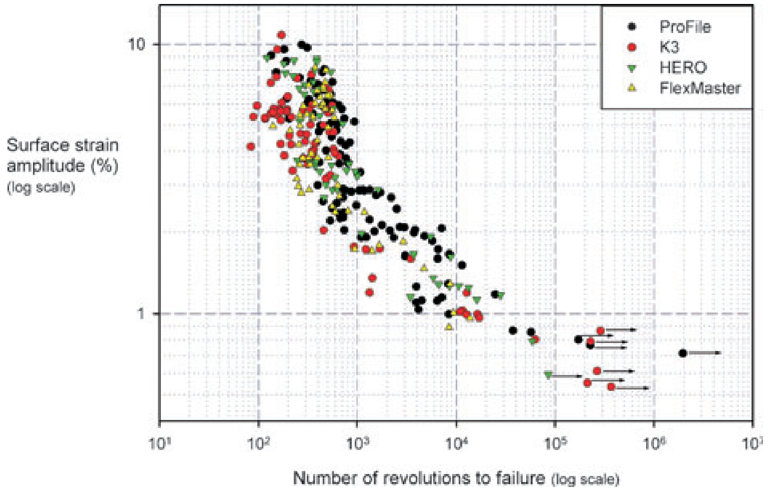

Figure 2 Fatigue lives of four brands of NiTi instrument tested under water. Symbols with an arrow indicate those which did not break when the test was abandoned.

The calculated surface strain amplitude ε_a was then plotted against N_f for each specimen on logarithmic scales; the LCF region was estimated to fall below 4000 cycles by noting the change in the slope of the chart (Fig. 2). A regression line was fitted to the LCF lives, because only the LCF region was of interest here. The slope of the regression line, which may be considered as the apparent fatigue-ductility exponent, as defined in the Coffin–Manson equation (Kocánda 1978, Collins 1993), was tested using one-way analysis of variance (one-way ANOVA) in software (SPSS for Windows 11.0; SPSS, Chicago, IL, USA) for difference between brands. The number of crack initiation sites was also noted on each photomicrograph, the homogeneity of which number was tested (chi-square, $\alpha = 0.05$).

Results

A strain-life relationship, typical of metallic materials, was found for various brands of instrument tested (Fig. 2); that is, the number of revolutions borne by the instruments prior to breakage declined rapidly with the calculated maximum surface strain amplitude. An 'elbow' in the plot was discernible between 10^3 and 10^4 cycles; the LCF region was deemed to extend up to 4000 revolutions. A regression line was fitted to the LCF lives for each brand of instrument (not shown). The slope of the line, i.e. the apparent fatigue-ductility exponent, was found to range between −0.40 and −0.58 ($P < 0.01$); the difference was not significant between groups (one-way ANOVA, $P > 0.05$) (Table 2).

Table 2 Apparent fatigue-ductility exponent derived from the LCF lives ($N_f < 4000$ cycles) for each brand

Group	No.[a]	Fatigue-ductility exponent c, ± SE[b]	Coefficient of determination
PF	87	−0.56 ± 0.04	0.66
K3	63	−0.41 ± 0.06	0.47
HE	40	−0.56 ± 0.07	0.62
FM	50	−0.40 ± 0.10	0.26

[a]This number excluded those which did not break when the test was interrupted, or with $N_f > 4000$ cycles.
[b]There was no statistically-significant difference between groups (one-way ANOVA, $P > 0.05$).

Fractographically, the crack origins, and areas showing microscopic fatigue-striations and dimple rupture, could be identified on all fracture surfaces. Nearly all ProFile instruments (Dentsply Maillefer) demonstrated crack initiation at the cutting edge or the 'radial land' region (Fig. 3). For the K3 (Sybron Endo) group, crack initiation appeared somewhat erratic; origins of fatigue-cracking could be found not only at the cutting edge, but also at various places along the flute (Fig. 4). The HERO Shaper (Micro-Mega) (Fig. 5) and FlexMaster (VDW) (Fig. 6) instruments generally had the crack origins located at the cutting edge except when a subsurface void or inclusion was present elsewhere. The number of crack initiation site was significantly different between groups ($P < 0.05$), with K3 (59%) having the highest incidence of multiple crack origins, followed by FlexMaster (55%), HERO (35%) and ProFile (23%) instruments (Table 3).

Discussion

The effective surface strain amplitude imposed on the instrument during the test was determined by an engineering formula for a beam under bending. It has been shown that the fatigue behaviour of a NiTi instrument is typical of NiTi alloys when the analysis is based on the strain amplitude (Cheung & Darvell

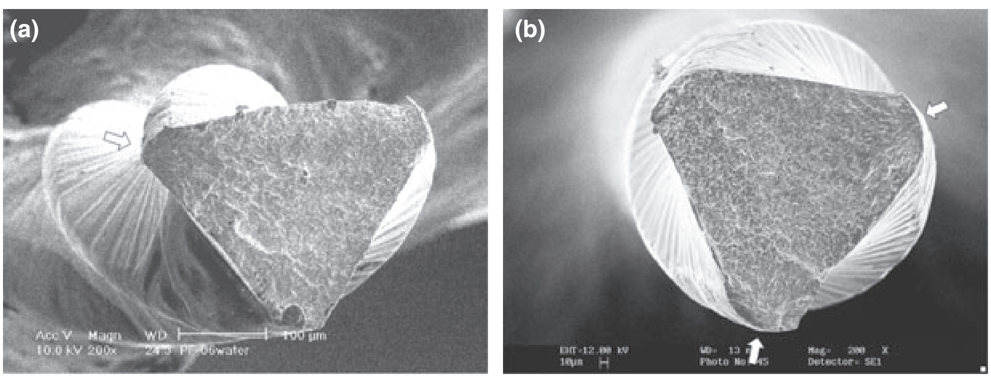

Figure 3 (a, b) Photomicrographs of the fracture cross-section of ProFile instruments; crack origins are indicated (arrow).

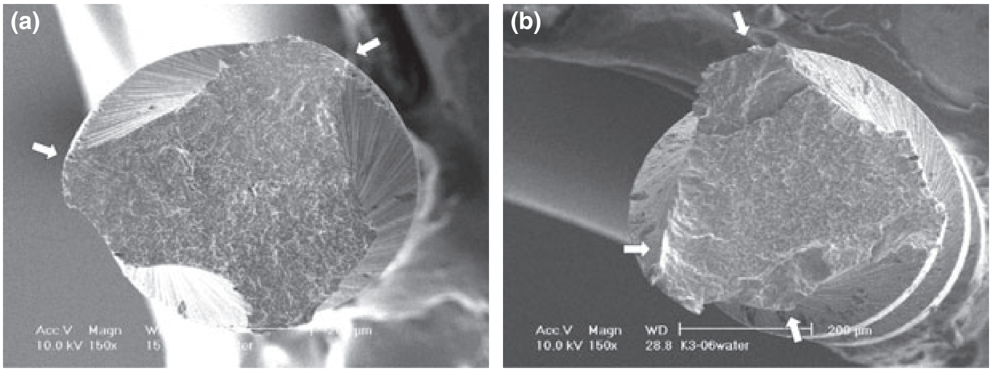

Figure 4 (a, b) Photomicrographs of the fracture cross-section of K3 instruments; crack origins are indicated (arrow).

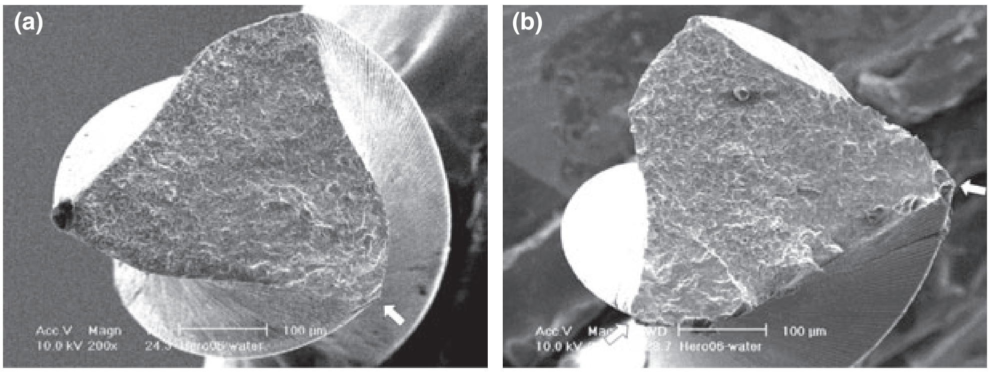

Figure 5 (a, b) Photomicrographs of the fracture cross-section of HERO Shaper instruments; crack origins are indicated (arrow).

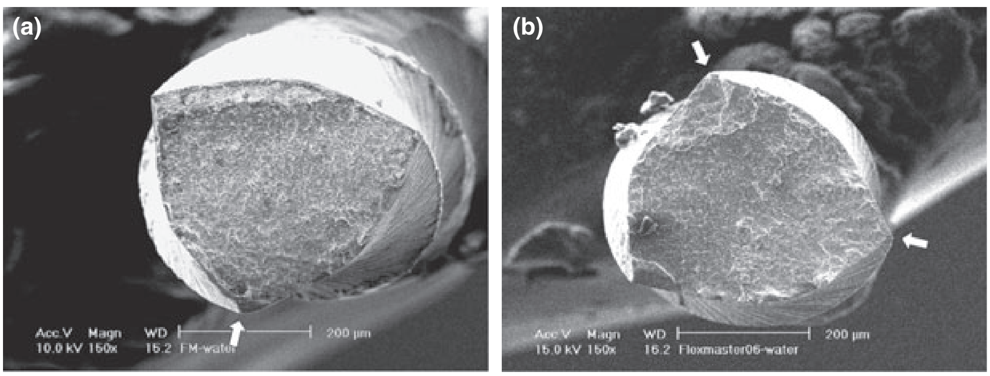

Figure 6 (a, b) Photomicrographs of the fracture cross-section of FlexMaster instruments; crack origins are indicated (arrow).

2007a). Thus, the strain amplitude, a measurement of the amount of repeated deformation, is obviously better than either the angle or radius of curvature, or the instrument size for correlation with the fatigue life. In this present study, the engine-files were strain-cycled under water, which was intended to resemble the clinical situation in which root canals are flooded with an irrigant solution during treatment. Clinically, irrigant solutions are stored at room temperature and are used in teeth that have been isolated by rubber dam. Typically, copious amounts of irrigant are used, as recommended in all relevant textbooks. The high heat

Table 3 Number of crack origins identified for each brand

Group	No. of crack origins	No. of instruments[a] (% of subtotal)	Subtotal	No. of unavailable data (contaminated/not broken)	Total
PF (a)	1	78 (77)	101	2/3	106
	2 or more	23 (23)			
K3 (b)	1	28 (41)	69	0/5	74
	2 or more	41 (59)			
HE (a,c)	1	32 (65)	49	1/1	51
	2 or more	17 (35)			
FM (b,c)	1	23 (45)	51	4/0	55
	2 or more	28 (55)			

Groups with the same letters in parenthesis were not significantly different from each other (pairwise comparisons using Fisher's exact test, $P < 0.01$).
[a]Comparison between instruments: $\chi^2 = 30.84$, df = 6, $P < 0.0001$.

capacity of water effectively maintains the temperature of the instrument, both here and in the clinical setting, and thus testing in water at room temperature is judged to be appropriate and the results applicable to the clinical situation (especially when one chooses to use an inert solution as the irrigating agent). There may be concern that there will be corrosion-fatigue when sodium hypochlorite, a common agent used in root canal treatment, is used as the irrigant. Indeed, there has been a report (Berutti *et al.* 2006) describing the deleterious effect of immersing the entire instrument in hypochlorite on the fatigue life; however, immersing only the NiTi portion of the instrument (i.e. the handle not immersed) in 5% hypochlorite did not result in any difference. Further investigation of the effect of hypochlorite is warranted.

The values of the apparent fatigue-ductility exponent ($-0.40 < c < -0.56$) determined for the various brands of instrument are in agreement with the general value reported for superelastic NiTi alloys (Tolomeo *et al.* 2001, Pelton *et al.* 2004). This is not surprising because the manufacturing process merely imparts a shape to the instrument; none of these commercial products have (apparently) received any post-manufacture heat treatment or special surface treatment by the manufacturer. The LCF life of various instruments did not seem to be affected by the instrument design. The fact that the bulk material properties, ductility in particular, have a strong influence on the LCF behaviour (Reed-Hill & Abbaschian 1992, Schijve 2001) may partly explain such observation. In contrast to high-cycle fatigue where the time taken for the initiation of a fatigue-crack is much longer than the steady crack-growth period (ASM International 1996), LCF is characterized by exceeding the yield point of the material, leading to extensive, local, plastic deformation, and hence early cracking. Ductility of the material would help to blunt a crack tip and so retard fatigue-crack propagation (Ritchie 1999). As most endodontic manufacturers in the USA and Europe use nickel-titanium raw wires of very similar, if not the same composition, instruments from those various manufacturers possess similar mechanical properties. This may at least partly explain the lack of difference between the various brands of instrument examined.

The crack origins were usually found at the cutting edge or 'radial land' region in most instruments. This is to be expected because when a circular beam is bent, its outermost fibres are subjected to the greatest stress and strain. Indeed, the first fatigue-crack often is initiated at the surface (when there is no major internal flaw or stress-concentration feature elsewhere) (Kocánda 1978, Schijve 2001). There seemed to be some effect of the cross-sectional shape on crack initiation with some difference between brands in the number of crack origins. For the one brand of instrument with an irregular cross-sectional shape (K3; SybronEndo, Orange, CA, USA), crack initiation occurred at a corner along the flute in some specimens (e.g. Fig. 4b), which might be a result of stress concentration. Despite the difference in the number of crack origins observed, there was little difference in the overall fatigue life in the LCF region, suggesting that the cross-sectional area or shape of the instrument is not the main determinant of the LCF life. In a related study (Cheung & Darvell 2007b), it has been shown that the distance travelled by the fatigue-crack towards the centre of the fracture cross-section (i.e. leading to fatigue fracture) seems to be correlated with surface strain amplitude, instead of the cross-sectional area. Given the importance of surface condition on the fatigue-crack initiation process, altering the surface smoothness or hardness of the instrument may be worth investigating.

Conclusions

The LCF life of NiTi instruments declines with an inverse power function dependence on surface strain amplitude, but is not affected by the cross-sectional shape of the instrument.

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