An overview of the mechanical properties of nickel–titanium endodontic instruments

HUIMIN ZHOU, BIN PENG & YU-FENG ZHENG

Differences in mechanical properties between endodontic instruments might be related to the chemical composition, phase constitution, or fabrication process of nickel–titanium (NiTi) endodontic instruments. An awareness and knowledge of the mechanical properties of NiTi endodontic files and their association with the metallurgical properties is useful for clinicians to understand the behavior of NiTi instruments in root canals and help them to make decisions regarding which instruments are appropriate for root canal therapy under certain clinical conditions. This review article summarizes the mechanical properties of NiTi endodontic instruments including the flexibility, torsional resistance, flexural resistance, and cyclic fatigue of the conventional superelastic NiTi instruments and the most recently developed novel NiTi instruments with martensite and R-phase. The influence of the metallurgical properties and the thermomechanical processing on the mechanical properties are discussed.

Received 27 July 2013; accepted 17 September 2013.

Introduction

Nickel–titanium (NiTi) alloy has been used in endodontics for almost 25 years and has brought a major breakthrough to root canal therapy since Walia et al. (1) employed a nickel–titanium arch wire to fabricate a root canal file in 1988. NiTi endodontic instruments with superelasticity (SE) have gained extensive popularity amongst clinicians due to their higher flexibility and greater torsional resistance than the traditional stainless-steel ones (1,2). Therefore, an increasing number of superelastic NiTi endodontic files with various geometry designs (cross-sectional shape with or without “radial lands” or sharp cutting edges, constant or variable pitch, and progressive or constant taper) have been developed (3–5). However, the undesirable and unexpected separation of NiTi endodontic rotary files during root canal instrumentation caused by cyclic fatigue and/or torsional overload still remains a serious concern and drawback in clinical use. In recent years, novel kinds of NiTi endodontic files fabricated by proprietary thermomechanical processes such as M-wire files (e.g. ProFile GT Series X, ProFile Vortex, and ProFile Vortex Blue: Dentsply Tulsa Dental Specialties, Tulsa, OK, USA), controlled memory (CM) files (e.g. HyFlex CM: Coltene Whaledent, Cuyahoga Falls, OH and TYPHOON Infinite Flex NiTi: Clinician’s Choice Dental Products, Milford, CT, USA), and R-phase wire [e.g. Twisted files (TF) and K3XF files: SybronEndo, Orange, CA] have been introduced and have shown improved flexibility and cyclic fatigue resistance compared to the traditional superelastic NiTi files (6–10).

The mechanical properties of NiTi endodontic instruments including flexibility, torsional resistance, and flexural fatigue are fundamental requirements of endodontic instruments for successful use. The flexibility is beneficial for maintaining the original shape of root canals, especially for the ones with severe curvatures. Adequate torsional resistance and flexural fatigue resistance favor reducing the occurrence of the
intradental separation. Thus, flexibility and resistance to fracture constitute properties expected for an ideal root canal file (11,12). From a material point of view, the properties of NiTi alloys depend on their chemical composition, phase constitution, and fabrication procedures, among which the metallurgical properties including the chemical composition and phase constitution are the internal factors and the fabrication procedures such as cold working, annealing, and aging are the external factors of the mechanical properties for NiTi endodontic files. Most research efforts to date have been devoted to the characterization of the metallurgical and mechanical properties of both the conventional superelastic NiTi instruments and the more recently developed novel NiTi instruments (13–17). In contrast, the relationship between the metallurgical properties and the mechanical properties of these instruments has been given relatively little attention. The knowledge of the mechanical properties and their association with the metallurgical properties of NiTi rotary instruments is helpful for clinicians to understand the behavior of NiTi instruments in root canals and to make decisions regarding which instruments are appropriate for root canal therapy. Therefore, this review is intended to summarize the mechanical properties of the traditional superelastic NiTi instruments and currently developed novel NiTi instruments, as well as their internal and external influencing factors, with a special focus on the influence of metallurgical properties on their mechanical properties.

**Deformation mechanism of NiTi alloy**

Nickel–titanium (NiTi) alloy is a kind of intermetallic compound with superior ductility, which is a stoichiometric compound of Ti and Ni. It is usually called NITINOL, where Ni is for Nickel, Ti is for Titanium, and NOL is for Naval Ordnance Laboratory, the place where Buehler and his co-workers discovered this alloy. It also called equiatomic NiTi alloy due to its one-to-one atomic ratio of nickel to titanium and referred to as NiTi alloy, respecting the metallurgical terminology of solid solutions with 55 wt% Ni and 45 wt% Ti (18). It is worth noting that only the NiTi alloys with nearly equiatomic ratio possess the unique superelasticity (SE) and shape memory effect (SME) because of the narrow solubility range of the “TiNi” phase at 500°C or below, which becomes negligible at about 500°C (19). That is why most of the NiTi alloys used for endodontic instruments are at a nearly one-to-one atomic ratio of nickel to titanium, which is equal to approximately 56 wt% nickel and 44 wt% titanium (2,7,20,21).

The illustrative tensile stress-strain curve of equiatomic NiTi alloy is shown in Figure I. The mechanical behavior of near-equiatomic NiTi alloy exhibits eight stages and can be classified into three distinctive types according to the mechanism of its deformation, i.e. stress-induced martensitic (SIM) transformation (stage IV), martensite reorientation (MR, stage VI), and the distinct stage of yielding by plastic deformation (stage VIII) (22). The stress plateau in the stress-strain curve is an inelastic deformation associated with either SIM or MR, depending on the starting structure (e.g. deformed in austenitic state via SIM and deformed in martensitic state via MR) (23). The superelasticity is associated with SIM and the shape memory is associated with MR.
The superelasticity is one of the most important reasons for the use of NiTi alloys in endodontic instruments because it endows NiTi endodontic instruments with superior flexibility and allows them to follow the complex anatomy of root canals, resulting in reduced ledging and perforations (24). The superelasticity or pseudoelasticity (PE) of near-equiatomic NiTi alloy arises from the reversible stress-induced martensitic transformation. This process is driven by stress and influenced by the temperature difference between the working temperature and \( T_f \), the critical finishing temperature for the reverse transformation of martensite on heating (25). A stress-induced martensitic transformation can be observed within the temperature range between \( M_s \), the critical starting temperature for the forward transformation of austenite on cooling, and \( T_d \), a critical temperature at which the critical stress for stress-induced martensitic transformation equals that of the plastic deformation of the austenite (26). The superelasticity of NiTi allows deformations of as much as 8% strain to be fully recoverable, in comparison with a maximum of less than 1% with other alloys such as stainless-steel (2). To utilize the superelasticity of NiTi alloys, it should be in the austenitic state, which is the high-temperature parent phase of NiTi alloy with B2 (CsCl) type ordered structure. Many conventional NiTi endodontic files were made of superelastic NiTi alloy, such as ProFile (Dentsply Maillefer, Ballaigues, Switzerland) and ProFile GT (Tulsa Dental Products, Tulsa, OK), Mtwo (VDW, Munich, Germany), LightSpeed (LightSpeed Technology, Inc., San Antonio, TX), Quantec (Analytic, Orange, CA), Hero 642 (Micro-Mega, Geneva, Switzerland), and K3 (SybronEndo, Orange, CA). All of these conventional rotary instruments are used clinically in the austenitic state (i.e. at body temperature). They can be inserted easily in the root canals due to the high elasticity and flexibility, and when an external stress is applied due to the torsion stress and the file friction against the canal inner walls, the stress-induced martensitic transformation occurs, giving rise to a more elastic material with a high ultimate tensile strength (27). In this way, the files work with a constant cutting stress, even in a much-curved canal. It is the reason why NiTi files are advantageous in maintaining the shape of root canals compared to stainless-steel ones.

Another mechanism of the mechanical deformation of NiTi alloys is the martensite variant reorientation (stage VI), which is related to the shape memory effect of NiTi alloys. When the NiTi alloy is deformed in the martensite state, it undergoes a strain, which is completely recoverable upon heating. This behavior is called the shape memory effect. Deformation via martensite reorientation may be observed at temperatures below \( A_s \), the critical starting temperature for the reverse transformation of martensite on heating (26), and be completed at \( A_f \). This process is thermally driven and influenced by the transformation temperatures. Peters et al. (6) pointed out that instruments in the martensitic phase can be easily deformed and will recover their shape when heated beyond the transformation temperature. The martensite phase of the NiTi alloy is a low-temperature phase with monoclinic structure (B19'), which possesses a relatively lower Yong’s modulus (20 to 50 GPa) and yield strength (138 GPa) than the austenite (40 to 90 GPa and 379 MPa, respectively) (28–30). This indicated that the martensite is easily deformed at quite a low stress, whereas the austenite has much higher yield and flow stresses. Besides being more flexible than austenite, the martensite favors reducing the risk of file fracture under high stress because it can be plastically deformed rather than broken. Therefore, much effort has been devoted to introduce martensite into commercial NiTi endodontic instruments such as M-wire and CM endodontic instruments. The M-wire NiTi endodontic instruments (Dentsply Tulsa Dental Specialties) including ProFile GT-X, ProFile Vortex, and ProFile Vortex Blue are manufactured from the superelastic NiTi wires containing martensite. Several studies on the performance of the commercial instruments made with M-wire NiTi suggested enhanced flexibility and fatigue resistance (6–8,20). The CM files such as Hyflex CM file (Coltene Whaledent, Cuyahoga Falls, OH) and TYPHOON Infinite Flex NiTi files (Clinician’s Choice Dental Products, Milford, CT, USA) are used in the martensitic state and possess the shape memory effect. These files can return to their original shape by autoclaving after use in curved canals. Moreover, the manufacturer of Hyflex CM files claims that their instruments are up to 300% more fatigue-resistant and have no rebound, and can regain their shape after sterilization. Some studies have confirmed the higher fatigue resistance of Hyflex CM files and Typhoon CM files when compared with conventional NiTi instruments (7,8,31,32).
In addition, there is a special type of martensitic transformation called R-phase transformation in NiTi alloys (stage II and III in Fig. 1). The R-phase is a rhombohedral phase that is incommensurate with the cubic B2 phase (33). The R-phase transformation occurs prior to the B2-B19′ transition and exhibited the characteristics of thermoelastic martensitic transformation, i.e. shape memory and superelasticity effects. Thus, the R-phase transformation can be temperature-induced and stress-induced in NiTi alloys. Compared with the martensite/austenite transformation in NiTi, the recoverable strain of the R-phase/austenite transformation (approximately 0.5%) is smaller and the temperature hysteresis is extremely small (1–2 K) (19). Moreover, the cyclic stability of the R-phase/austenite transformation is excellent (34) and the Young’s modulus of the R-phase is typically lower than that of austenite. The appropriate choice of thermomechanical treatments can make the R-phase transformation occur due to the fact that the R-phase transformation tends to occur when precipitates or dislocations exist. The aging of Ni-rich NiTi alloy at the proper temperature may cause the precipitation of the Ti3Ni4 phase, and thermomechanical treatment (heat treatment after cold working) of NiTi alloy may create rearranged dislocation structures (19). Therefore, utilization of the R-phase transformation in the design and fabrication of NiTi endodontic instruments has the potential to produce new, innovative endodontic instruments. The TF file is a NiTi rotary instrument manufactured with the R-phase alloy using a twisting method; it exhibits a higher fatigue fracture resistance than ground files as reported in preliminary studies (35–40). K3XF is another product that takes advantage of R-phase technology and was developed by the same company as TF files (SybronEndo); however, it is fabricated by a grinding process rather than a twisting process. A special heat treatment is performed on K3XF files after the grinding process, which not only enhances the flexibility and strength, but also modifies the crystalline structure of the alloy to accommodate some of the internal stress caused by the grinding process (10,41). The manufacturer claims that K3XF files possess the basic features of the original K3 files plus an extraordinary new level of flexibility and resistance to cyclic fatigue owing to the proprietary R-phase technology. Recent studies (10,42,43) show that K3XF instruments have superior fatigue resistance compared with conventional superelastic NiTi instruments.

**Relationship between the metallurgical properties and mechanical properties of NiTi endodontic instruments**

The differences in the mechanical properties amongst NiTi endodontic instruments is due to the variety of materials and manufacturing conditions used, which affect their clinical performance (2,44–46). A NiTi alloy with a specific composition could have its mechanical properties optimized by adjusting the alloy’s microstructure via cold work and heat treatment (47). Although the detailed thermomechanical process is unknown due to the protection of intellectual property, we can evaluate the influence of the thermomechanical treatments on the mechanical properties of NiTi endodontic instruments indirectly by analyzing the phase transformation behavior of the alloy. The characteristic transformation temperatures that can be manipulated by adjusting the chemical composition and heat treatment conditions play an important role in determining the alloy’s mechanical properties (48). From the material point of view, the NiTi endodontic files have taken advantage of different phases in the NiTi alloy, i.e. conventional SE instruments, R-phase instruments, and martensite instruments. To a large extent, the differences in mechanical properties between NiTi endodontic files lie in the properties of the phases that exist in the alloy, which are determined by the phase transformation temperatures. Therefore, one can study the influence of phase constitution on the mechanical properties of NiTi endodontic files, instead of the influence of thermomechanical processing. The typical metallurgical and mechanical properties of conventional NiTi and newly developed NiTi endodontic instruments are summarized in Table 1.

**Metallurgical challenges in endodontic instruments**

It is generally accepted that metallurgical properties have a dramatic impact on the performance of NiTi instruments. These properties include the composition, microstructure, and phase constitution of
<table>
<thead>
<tr>
<th>Properties</th>
<th>SE-NiTi File</th>
<th>EndoSequence</th>
<th>K3</th>
<th>ProFile GTX</th>
<th>Vortex</th>
<th>Vortex Blue</th>
<th>CM-Wire File</th>
<th>Typhoon CM</th>
<th>TF Fik</th>
<th>R-Phase File</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni content (wt%)</td>
<td>54.6(31)</td>
<td>56.0(31)</td>
<td></td>
<td>54.7(31)</td>
<td>54.2(42)</td>
<td>56(89)</td>
<td>52.1(31)</td>
<td>55.1(32)</td>
<td>17.6(32)</td>
<td>24.89(42)</td>
</tr>
<tr>
<td>)± Ni (wt%)</td>
<td>31.1(31)</td>
<td>29.6±2.4(30)</td>
<td>17.0(32)</td>
<td>17.6±1.76(31)</td>
<td>5.4±6.8(60)</td>
<td>3.88±3.21(31)</td>
<td>50.4(32)</td>
<td>51.7−55.9(52)</td>
<td>47−51.4(53)</td>
<td>18.9±1.7(51)</td>
</tr>
<tr>
<td>Microhardness (MPa)</td>
<td>352±10.5(54)</td>
<td>351±11.1(31)</td>
<td>339±29.5(55)</td>
<td>361±39(60)</td>
<td>376±18(52)</td>
<td>312±18(53)</td>
<td>436±10(99)</td>
<td>390±7.9(54)</td>
<td>35.1±27.6(32)</td>
<td>344.5±7.6(4)</td>
</tr>
<tr>
<td>Angle of rotation (°)</td>
<td>385±32(54)</td>
<td>7.39±55.7(6)</td>
<td>470−682(56)</td>
<td>336−346(7)</td>
<td>581.49−656.34(42)</td>
<td>1187−1412(56)</td>
<td>567±54(54)</td>
<td>457±47(54)</td>
<td>505−860(36)</td>
<td>609.0±15.8(65)</td>
</tr>
<tr>
<td>Bending moment at 45 degrees (g·cm)</td>
<td>110±8.4(54)</td>
<td>48.98(99)</td>
<td>46.01±3.9(7)</td>
<td>34−114(9)</td>
<td>333±39(5)</td>
<td>98.1±6.4(10)</td>
<td>27−94(4)</td>
<td>163−406(42)</td>
<td>31−90(56)</td>
<td>77±6(54)</td>
</tr>
<tr>
<td>Fatigue number of cycles to failure (NCF)</td>
<td>205.9±72.8(60)</td>
<td>552.5±91.54(61)</td>
<td>579±60.1(60)</td>
<td>459±64(45)</td>
<td>454±81(60)</td>
<td>551.5±100.7(60)</td>
<td>1142±179(64)</td>
<td>1609±269(54)</td>
<td>2565−157(26)</td>
<td>651±149(63)</td>
</tr>
</tbody>
</table>
NiTi instruments, and can be conveniently investigated by metallurgical laboratory techniques such as energy dispersive X-ray spectrometer (EDX), optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), normal differential scanning calorimeter (DSC), temperature-modulated DSC (TMDSC), and X-ray diffraction (XRD) spectrum or micro-XRD spectrum. These techniques are usually used together in order to form a more complete understanding of the metallurgical properties of NiTi instruments. For example, in the case of microstructure analysis, XRD spectrum can reveal the structure within approximately 50 μm of the surface (32), and DSC is usually used as a complimentary analytical technique that provides information on the phase transformation behavior. In addition, microstructural observation can further confirm the microstructure of the instrument. Figure 2 shows the typical microstructures of some NiTi instruments. The Typhoon NiTi file is a conventional NiTi instrument that has an austenitic microstructure. However, it shows lenticular martensite structure under an optical microscope at room temperature. Shen et al. explained this phenomenon by the possible existence of stabilized martensite in the conventional superelastic NiTi instruments (32), which was confirmed by DSC results.

Conventional NiTi instruments take advantage of the superelasticity of NiTi alloy and are used in the austenite phase under clinical conditions. Recently, NiTi instruments containing martensite or R-phases have attracted the considerable attention of researchers due to the fact that they can be deformed more easily than those in the austenite phase. Therefore, proprietary thermomechanical processing procedures have been used in order to optimize the structure of the NiTi wire blanks for rotary instruments (36-42). The details of the metallurgical properties of newly developed NiTi instruments can be found in a previous review (41).

Influence of composition

Most of the NiTi alloys used for endodontic instruments are made in a nearly one-to-one atomic ratio of nickel to titanium, which equals approximately 56 wt% nickel and 44 wt% titanium (2,48,62). However, subtle adjustments in the ratio of these two elements cause a dramatic change in the transformation temperature, which has a significant effect on its mechanical properties (7). The nickel content of a NiTi alloy has a great influence on the transformation temperatures; an increase of 0.1% will lower the phase transformation temperature by 12°C (7). The chemical composition of NiTi endodontic files is usually examined by EDX, which is a semi-quantitative chemical analysis and has been employed for both conventional NiTi instruments and the most recently developed NiTi instruments (11,21,27,31,55,63). However, EDX is not sensitive enough to detect slight changes in the composition of the alloy that can result in a large difference in the mechanical properties (50). Zinelis et al. (31) evaluated the elemental composition of 10 brands of NiTi endodontic instruments and discovered that Hyflex X-files exhibit a lower percentage of nickel by weight (52 wt% Ni) than the common 54.5-57 wt% Ni shown in the great majority of commercially available NiTi rotary instruments. This lower nickel content exerts an influence on the transformation temperature, resulting in the A_t temperature of over 47°C for Hyflex NiTi files (53).
Influence of phase constitution

The phase constitution of NiTi endodontic files under the service temperature plays an important role in determining the mechanical properties of the files. The characteristic transformation temperatures and the crystalline phases found in the various instruments are an indication that different heat-treatment procedures may have been applied during instrument manufacture (48). The transformation temperatures (M_s, M_f, A_s, and A_t) at which the crystal structure changes from austenite to martensite or vice versa are usually measured by DSC. If the temperature is above A_t, the NiTi alloy is fully austenite, which possesses superior superelasticity. If the temperature is below M_f, the alloy possesses a shape memory effect due to the phase constitution of fully martensite. The presence of some martensite facilitates the stress-induced martensitic transformation, which occurs at lower applied stresses. Thus, less stress is necessary to induce martensitic transformation at a higher M_s (45). Viana et al. (48) revealed that K3 instruments with a lower A_t temperature showed a higher bending moment due to the small amounts of martensite. If the temperature is above A_s and below A_t, or above M_s and below M_f, the alloy consists of austenite and martensite. In addition, DSC curves can provide more information about the phase transformation behavior upon cooling and heating such as one-stage phase transformation (B2-B19’) and multi-stage phase transformation (B2-R-B19’), which can further reveal the influence of the thermomechanical process. However, the results of DSC analyses in NiTi endodontic instruments are contradictory. As Bahia et al. (21) pointed out, the A_s temperature of unused ProFile instruments tested by Brantley et al. (13) was -33°C, which certainly should not be expected for NiTi superelastic alloys (64,65). This may be attributed to the unique form of NiTi endodontic files with complex flutes and small diameters. Therefore, other techniques are needed to confirm the results of DSC, such as XRD (13–17), micro-XRD (66), metallographic examination (17), and TEM (9,66). However, there are some limitations of each technique. Only the phase with an amount more than 3% in volume can be detected by XRD due to the restriction of the resolution of the technique. Miyai et al. (50) analyzed the phase constitution of similar instruments using DSC experiments and found that instruments with low transformation temperatures (Hero, K3) tended to show a higher maximum torque and higher bending load value than instruments with high transformation temperatures (EndoWave, ProFile, and ProTaper). They indicated that the mechanical performance of NiTi endodontic instruments may be closely correlated with the transformation behavior of the alloy.

Mechanical performance of NiTi endodontic instruments

Flexibility

Flexibility of endodontic instruments is a fundamental requirement (48) because it allows appropriate canal enlargement while maintaining the instrument centered within the canal (67), causing fewer undesirable changes in the shape of curved canals (11). The high flexibility of NiTi endodontic instruments comes from the combination of the low elastic modulus and unique superelastic properties (48,68), which means that NiTi files can undergo significant deformation without reaching their elastic limits and still return to their original form. Flexibility is influenced by chemical composition and heat treatment as well as geometric configuration (48). In laboratory studies, it is usually evaluated by the bending test because bending is the most representative loading caused by the curvature of the root canals (68). The flexibility is characterized by the bending moment at 45° using a testing apparatus built according to ISO 3630-1 specifications (77) or studied by load-deflection curves during the loading and unloading process using a cantilever bending apparatus, as shown in Figure 3. Low bending moment and high flexural stiffness is indicative of the high flexibility.

For conventional SE NiTi endodontic instruments, the influence of geometrical designs play a crucial role on the flexibility, such as the cross-sectional configuration, the depth of the flute, area of the inner core, and peripheral mass in cross-section (69). Viana et al. (48) found a linear relationship between the average bending moment and the instrument’s diameter and cross-sectional area at 3 mm from the tip for ProTaper Universal, K3, and EndoSequence instruments. It has also been reported by previous studies that the U-file design had the lowest flexural rigidity, compared with a “convex triangular” cross-section with or without an additional flute (69). A...
recent numerical analysis concerning the effect of pitch and cross-sectional characteristics indicated that the flexural stiffness is related to the center-core area and that a decrease in pitch will lower the flexural stiffness (70). However, for the newly developed thermomechanically treated NiTi endodontic instruments, flexibility is largely determined by the manufacturing processes. Hayashi et al. (45) found that the additional heat treatment of hybrid NiTi instruments was effective in increasing the flexibility of NiTi rotary instruments. As demonstrated by a previous study, the new manufacturing process possesses the capability to produce more flexible NiTi instruments (TF files) (35).

**Torsional resistance**

Torsion is one of the primary mechanisms responsible for the intracanal separation of NiTi endodontic instruments (71,72), which accounts for 55.7% of the failures of NiTi rotary instruments (71,72). It can be generated within the rotary file when the tip or some part of the instrument is locked against the canal wall while the shank of the file (driven by the handpiece) continues to rotate or is subjected to excessive pressure by the clinician (3,68). The tip fractures when the handpiece torque exceeds the ultimate strength of the metal (73). High torsional stiffness is desirable for the clinical performance of rotary files owing to the enhanced cutting efficiency and reduced torsional failure risk (11,74,75). In addition, the amount of rotation an endodontic file can withstand prior to failure reflects its ductility, which can be considered as a “safety factor” for endodontic files. It is easier to detect a deformation of the cutting spiral after having used a file with greater ductility; this helps to prevent failure of the file by allowing it to be discarded prior to breakage (76). The measurement of the torsional strength of root canal instruments is usually performed in a torsion meter according to the method proposed by ISO3630-1 (77) or ANSI/ADA Specification No. 28 for stainless-steel root canal reamers and files (41,77,78). The typical torque-angle curves are shown in Figure 4. As can be seen in the figures, two parameters (i.e. the maximum torque and angular distortion at the fracture of the instrument) are obtained from the test (42,74). The torsional resistance of a NiTi endodontic file is affected by material properties, manufacturing quality, and geometric design. Several studies have found that some thermomechanically treated NiTi instruments show similar torque at the fracture to that of conventional SE NiTi instruments (6,79,80). In contrast, the results of a recent study showed that Vortex Blue NiTi and M-wire offered functional advantages over conventional superelastic NiTi, and Vortex Blue showed improved fatigue resistance and flexibility compared with ProFile Vortex M-wire (54).

**Flexural fatigue resistance**

Cyclic fatigue occurs when a metal is subjected to repeated cycles of tension and compression that cause its structure to break down, ultimately leading to fracture (600). It is the main reason for the majority (93%) of broken instruments. The fracture caused by
cyclic fatigue of NiTi endodontic instruments is difficult to detect during clinical practice due to the invisible signs of permanent deformation during cyclic fatigue (81). That is why many attempts have been made to improve the resistance to cyclic fatigue for NiTi instruments, including novel thermomechanical processing and exploring new materials. The cyclic fatigue properties of NiTi endodontic instruments have been studied fairly extensively (36,38,44,82–96). The fatigue life is determined by two factors: the rate of crack initiation and the rate of crack propagation. It has been stated that M-wire instruments demonstrate superior resistance to fatigue-crack initiation compared with regular SE-wire files, owing to the better reorientation capability of the M variants (83). In addition, a hybrid microstructure with a certain proportion of martensite is more resistant to crack propagation than a fully austenitic microstructure due to the fact that the speed of fatigue crack propagation of austenite is much faster than martensite (83). However, there is not yet any specification or international standard to test the cyclic fatigue resistance of endodontic rotary instruments. The devices and methods used to investigate the in vitro cyclic fatigue properties of NiTi rotary endodontic instruments are based on various simulated root canals (artificial root canals) with different curvatures, such as a glass or metal tube, a grooved block-and-rod assembly, and a sloped metal block (91). It is worth noting that even a small variation in the parameters of the curvature followed by an instrument subjected to flexural fatigue may result in a significant influence on the results of the cyclic fatigue (91,92). Most of the artificial root canal models used for evaluating in vitro cyclic fatigue resistance have the drawback of the difference between the real trajectory of a NiTi instrument inside the artificial root canals and the predetermined curvatures, making it impossible to compare the cyclic fatigue between instruments of different sizes under different conditions. Plotino et al. (91–94) proposed a new model specifically constructed on the dimensions of the instrument tested to reduce the approximation in cyclic fatigue tests, which were made using a die-sinking electrical-discharge machining process. It has been stated that different NiTi rotary instruments may follow a precise and repeatable trajectory in terms of radius and angle of curvature (92).

Mechanical properties under combined loading modes

NiTi endodontic instruments used in clinical practice are subjected to both flexural fatigue and torsional load simultaneously during root canal preparation procedures, probably leading to instrument separation due to hybrid forces (97). Because bending is imposed by the root canal anatomy, in the case of blockage, it is also associated with torsion (68). Clinically, both cyclic fatigue and torsional failure probably occur simultaneously; however, most studies on the fracture simulation of NiTi files have been performed separately for cyclic fatigue or torsional failure (74,80,89). Several researchers have attempted to evaluate the effect of combined cyclic fatigue and torsional stress on the performance of NiTi rotary instruments (89,98–101). It has been reported that cyclic fatigue of approximate 75% may significantly reduce the torsional resistance of NiTi rotary instruments (8). Ulmann & Peters (100) found that cyclic pre-stressing significantly reduced torsional resistance in ProTaper finishing files, while ProTaper shaping files were largely unaffected. In a recent study, it was found that the combined stress of cyclic fatigue and torsional load compared to cyclic fatigue only resulted in statistically significantly different mean fragment lengths, independent of file diameter, alloy,
or cross-section. It suggested that stress was distributed from areas where torsional load was applied toward the area undergoing cyclic fatigue and implied that clinically a fracture resulting from only cyclic fatigue may not be distinguished from a fracture due to the combined stress from cyclic fatigue and torsional stress (101).

Conclusions

The differences in the mechanical properties amongst NiTi endodontic files depend mostly upon the properties of the phases that exist in the alloy, which is determined by the phase transformation temperature. Although the detailed thermomechanical process is unknown due to the protection of intellectual property, one can evaluate the influence of thermomechanical treatments on the mechanical properties of NiTi endodontic instruments indirectly by analyzing the phase transformation behavior of the alloy. From the material point of view, NiTi endodontic files have taken advantage of the different phases in NiTi alloy, i.e. conventional SE instruments, R-phase instruments, and martensite instruments. Compared with SE NiTi instruments, the introduction of martensite and R-phases into the phase constitution of recently developed thermomechanically treated NiTi endodontic instruments has produced improved flexibility and fracture resistance.

Acknowledgements

The authors deny any conflict of interest related to this study. This work was supported by the Fundamental Research Funds for the Central Universities of China (No. HEUCF201310014) and the Natural Science Foundation of Heilongjiang Province (ZD201012).

References


73. Martin B, Zelada G, Varela P, Bahillo JG, Magán F, Ahn S, Rodríguez C. Factors influencing the fracture...