

## | Nickel-Titanium Rotary File Systems: What's New?

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### ABSTRACT

Ever since their introduction, nickel–titanium (NiTi) alloys have continued to revolutionize the field of endodontics. They have considerable advantages over the conventional stainless steel file in terms of mechanical properties. However, despite of their superior mechanical properties, NiTi alloys still pose some risk of fracture. Consequently, there has been considerable research conducted to investigate the mechanisms behind the occurrence of these procedural errors. Since the last decade, different proprietary processing procedures have been introduced to further improve the mechanical properties of NiTi alloys. These treatments include thermal, mechanical, electropolishing, and recently introduced electric discharge machining. The main purpose of these treatments is to impart a more martensitic phase into the files at normal body temperature, so that the maximum advantage of flexibility can be obtained. These heat-treated instruments also possess improved cyclic fatigue resistance when compared to conventional NiTi alloys. NiTi alloys can be subclassified as the instruments mainly containing austenitic phase (conventional NiTi, M-wire, R-phase), and those containing martensitic phase (controlled memory wire, ProTaper Gold, and Vortex Blue). Instruments based on austenitic alloys possess superelastic properties due to the stress-induced martensitic transformation. Contrary to this, martensitic alloys can easily be deformed due to phase transformation, and they can demonstrate the shape memory effect when heated. This review discusses the different phase transformations and heat treatments that the NiTi instruments undergo.

**Keywords:** Austenite phase, controlled memory, martensite phase, nickel–titanium (NiTi) alloys, R-phase, thermo-mechanical treatment

### HIGHLIGHTS

- Nickel–titanium (NiTi) wires have gained a special place in commercial applications in dentistry because of their shape memory effect, biocompatibility, and corrosion resistance.
- When stress is placed on a NiTi wire, the austenite form is converted to the martensite (stress-induced martensite) form, which can accommodate greater stress without increasing the strain.
- This review discusses different phase transformations and heat treatments the NiTi instruments undergo.
- It also discusses the different types of newly introduced file systems and their clinical implications.

### INTRODUCTION

The introduction of nickel–titanium (NiTi) alloys in the late 1980s led to a revolution in endodontics as these files were shown to have considerable advantages over stainless steel (SS) files, especially in relation to the safety of instrumentation (1). NiTi files were able to overcome the issue of rigidity and low resistance to cyclic fatigue associated with stainless steel instruments. Other than the advantage of increased flexibility and shorter treatment time, NiTi wires also resulted in fewer procedural errors such as zipping, ledges, or transportation due to their superelasticity, compared with SS files (1, 2).

NiTi wires have gained a special commercial applications in dentistry because of their shape memory effect, and corrosion resistance. These properties of the alloy occur as a result of transition from the austenite to martensite form. This transformation requires “twinning,” which is a reversible atomic process that divides the lattice into two symmetric parts at an angle and allows reduction of strain during the transformation phase (3).

### Phase Transformations

The NiTi alloys used for manufacturing of the endodontic instruments contain approximately 56% (wt) of nickel and 44% (wt) of titanium. (4) However, even a 0.1% change in the composition of these alloys can result in a 10°C change in the transformation temperature, which can subsequently af-

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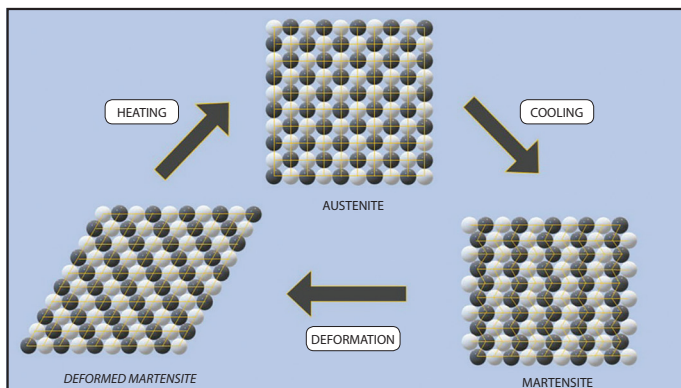
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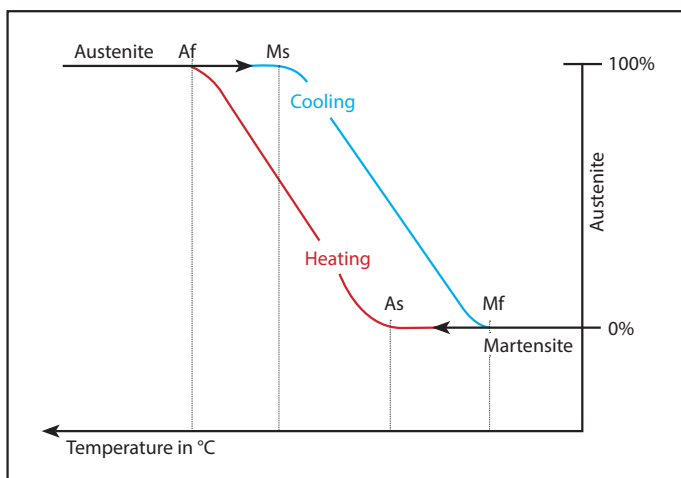
fect the mechanical characteristics of these alloys (5). At room temperature, these alloys are in the austenite form, which is a body-centered cubic structure (6). On cooling, the austenite form becomes a monoclinic structure called martensite (Fig. 1) because of a classic linear thermal contraction.

On further cooling down to  $M_s$ , that is, "Martensite Start" temperature, the contraction accelerates (7). However, when it is further cooled, the contraction rate becomes linear again until a certain point, that is, the "Martensite Finish" ( $M_f$ ), indicating the point where the proportion of martensite phase in the alloy reaches 100%. Reheating this martensite phase will eventually reverse the process and yield an austenite form (Fig. 2). An intermediate phase, that is, the R-phase, or "Rhomboidal phase", occurs on cooling before the martensitic transformation is complete (8).

When the external stresses are placed on a NiTi wire, the austenite form is converted to martensite (stress-induced martensite) form, which can accommodate greater stress without increasing the strain (up to 8%). As a result, a NiTi file has transformational elasticity, also known as superelasticity, or the ability to return to its original shape after being de-



**Figure 1.** Martensitic transformation: Pseudoplastic behavior of NiTi is based on austenite and martensite crystal configurations, which depend on temperature



**Figure 2.** Temperature hysteresis in NiTi alloys. ( $A_s$ ) austenite start temperature; ( $A_f$ ) austenite finish temperature; ( $M_s$ ) martensite start temperature; ( $M_f$ ) martensite finish temperature

formed (9). The stress-induced martensitic state is not stable at room temperature, so an immediate retransformation from the martensitic to the austenite phase occurs once the stress is released. This leads to a spring-back of the endodontic instrument to the original shape when it is removed from the canal (10).

A stress-induced change without permanent deformation for up to 8% strain is possible in NiTi alloys, as opposed to 1% in stainless steel (11). On releasing the stress, the martensite form reverts back to the original shape, that is, the austenite form (12).

### Superelasticity

NiTi alloys show the phenomenon of superelasticity where the stress remains constant, despite the increase in strain up till a certain range. Their superelastic property is caused by the austenite transforming into the martensite form. The strain remains constant during this transformation until the whole NiTi mass has converted to the martensite form, which would indicate that the superelasticity phase has ended (13). If deformation is continued beyond this point, the stress/strain curve will take the shape of classic relationship as the potential of the crystals in the structure to absorb strain is exhausted (8). However, if the plastic deformation limit is not reached, the deformation will remain reversible.

### Fracture mechanisms

NiTi instruments possess a risk of separation or fracture during use because of torsional or cyclic fatigue (14). Distortion of rotary NiTi files is often not visible without magnification. Consequently, these instruments can fracture without any warning signs as opposed to SS instruments where distortion can be perceived easily (15). Cyclic fatigue occurs due to the instrument rotating in a curved canal and generating repetitive tension/compression cycles that eventually lead to metal fatigue (16), whereas torsional fatigue is a result of different parts of the file rotating at different speeds. Clinically, torsional fatigue is the result of the instrument tip binding to the canal dentin, whereas the shank continues to rotate, creating a torque that results in torsional fracture (17). Torsional fatigue resistance is basically how much a file can twist before fracturing. This property is desirable during the use in a narrow and constricted canal where torsional load would be high during use.

Manufacturers are constantly trying to develop changes in NiTi rotary systems to improve the mechanical properties of these instruments, especially the fatigue resistance. One of the changes incorporated was heat treatment of these alloys, which produced instruments with superior mechanical properties (18). Other methods used produced instruments with different cross-sectional designs, or incorporated new manufacturing processes (19).

### Thermal treatments

Thermal treatments aim to affect the transition temperatures of the NiTi alloys and subsequently modify the fatigue resistance, whether it is torsional or cyclic fatigue (20). A proprietary thermal treatment is applied to the alloy during the R-phase when it undergoes martensite transformation. This

heat treatment maintains a crystallographic structure and apparently gives these files a higher fracture resistance and increased flexibility (21). Recently, manufacturers have developed NiTi superelastic alloys with a special heat treatment so that these NiTi alloys have a stable martensite phase in different clinical conditions. There are kinds of heat-treated NiTi alloys available: M-wire, R-phase, and CM wire.

The M-wire was introduced in 2007, and is essentially a thermally processed NiTi alloy that is stable at body temperature. It was developed via thermo-mechanical processing and contains three crystalline phases: deformed and micro-twinned martensite, R-phase, and austenite (6). The presence of the martensite phase improves the fatigue resistance of the file, but at the expense of hardness, which prompts the need for different surface treatments (22). Examples of M-wire files in market are ProFile GT series, Vortex files, ProTaper Next, Reciproc, and WaveOne. Literature reports a significantly improved cyclic fatigue resistance of M-wire, for example, ProTaper Next in comparison with conventional NiTi instruments. However, many studies show no difference in cyclic fatigue of M-wire and conventional NiTi files (23-26).

The other crystalline phase, that is, the R-phase (pre-martensitic) occurs along a very narrow temperature range on the heating or cooling curve between martensitic and austenitic forms. These instruments have increased resistance to cyclic fatigue along with greater flexibility than conventional NiTi files (27). An example is the twisted file (TF), which is manufactured using the twisting method. The basic austenite phase is transformed into the R-phase by heating and cooling. Serial heating and cooling would convert the twisted R-phase back to the austenite crystalline phase, which would become superelastic while stressed. This treatment can result in increased cyclic fatigue resistance of TF (11). However, literature reports that the R-phase instrument has a lower torsional strength than conventional NiTi files (28-31).

CM wires were introduced in 2010. They have a lower nickel content (52% wt.), as compared to other NiTi files. To incorporate extreme flexibility, these files undergo special thermo-mechanical treatment that also improves the shape memory effect of these files. Consequently, they do not have the rebound effect after unloading, and their original shape is restored after heat application or autoclaving procedure. Clinically, this incurs the benefit of pre-bending this file before placing in a curved canal, especially with patients with limited mouth opening. The CM wire has a stable martensite phase because the austenite finishing temperature is above the working temperature. This implies that thermally processed controlled memory alloys would mostly or totally be in the martensite phase at body temperature (32) (Fig. 3). CM instruments also have increased resistance to cyclic fatigue (300%–800% more fatigue resistant) because of their unique manufacturing process as they do not rebound to their original shape (33). However, they have one major drawback of increased tendency of permanent plastic deformation during use. Due to this weakness, these instruments are recommended for single use only (34). Some commercial brands of CM files include Hyflex CM, Thyphoon Infinite Flex NiTi Files, V-Taper 2H, and Hyflex electrical discharge machining (EDM).



**Figure 3.** Comparison of austenitic (ProTaper Next) and martensitic NiTi files (CM wire). (a) The austenitic NiTi file cannot be bent at room temperature; (b) The martensitic file can be bent at room temperature

### Surface treatments

When electric current is used to deposit metallic ions on one of the electrodes, the process is called electroplating. Any electrochemical process that would aim to reduce the surface irregularities of a material is known as electropolishing (8). Physical vapor deposition is a process whereby NiTi instruments are coated with a thin layer of titanium nitride. This results in an improved cutting efficiency and corrosion resistance without affecting the superelasticity of these instruments (35).

### Recently introduced NiTi file systems

BT-RaCe (FKG Dentaire) is a new file system introduced in 2013, derived from conventional austenite NiTi. These files have characteristic uniform triangular cross section and a blunt tip design called the booster tip. They undergo a surface electrochemical treatment that increases the resistance to cyclic fatigue (36). The booster tip is claimed to reduce the occurrence of deviation and transportation. This specialized tip is the unique feature of the BT-RaCe system that allows it to track canal curvatures with less stress and increased safety. Burklein et al. compared root canal preparations using the ProTaper Next and BT-RaCe systems and found no significant differences between them in canal transportation and straightening. The triangular cross section design has the tendency to make the instrument more flexible than other cross section designs (21, 37).

Hyflex CM (Coltène/Whaledent) is a NiTi rotary system that was first manufactured in 2011, and it is the first thermo-mechanically treated NiTi endodontic alloy. NiTi files made up

of CM wire do not have superelastic properties, neither at room temperature nor at body temperature in comparison to conventional NiTi files (22). The austenite finish temperature of Hyflex CM is 47–55°C, which is above the intracanal temperature (38). These files are reported to have a 300% times higher resistance to cyclic fatigue than conventional NiTi systems (38–41). This system tends to reduce the canal straightening effect due to its controlled memory effect. Studies have confirmed the reduced canal straightening of Hyflex CM when compared to other file systems (39, 40, 42). Instruments based on the CM wire also have an increased flexibility compared to M-wire and other conventional NiTi instruments (43–46). They also have increased cutting efficiency in lateral action compared to conventional NiTi systems, in spite of having greater flexibility (47, 48).

All these characteristics of Hyflex CM are attributed to the greater proportion of the martensitic component in the alloy (39, 40). The files of this system consists of various cross-sectional designs and tapers, that is, triangular (sizes 25,.08 taper and 20,.06 taper) and quadrangular (sizes 20,.04 taper, 25,.04 taper, 30,.04 taper, and 40,.04 taper) (49).

The Hyflex EDM (Coltène-Whaledent) file system introduced in 2016 is considered as an evolution of the Hyflex CM, as Hyflex EDM is produced with CM alloy and uses the EDM technology. EDM is a recognized noncontact machining process that allows a precise quantity of material removed via pulsed electric discharge. (50) Work pieces are machined in the EDM manufacturing process by generating a potential between a work piece and a tool. The sparks produced in this process cause the surface layer of the material to melt and evaporate (51). This creates a unique surface of new NiTi files and provides them with excellent mechanical properties by giving the instruments a rough and hard surface and increasing their cutting efficiency (52, 53). The transformation temperatures of Hyflex EDM are found to be higher compared to Hyflex CM. According to the X-ray diffraction analysis, Hyflex EDM consists of martensite and substantial amounts of R-phase, whereas Hyflex CM has a mixture of martensite and austenite phases (54). The lack of austenitic phase in Hyflex EDM could be due to its raised austenitic start temperature (as ~42°C) that prevents the formation of austenite at room or body temperature (38, 54). Hyflex EDM still has a higher hardness than conventional CM wires, despite absence of or reduced austenitic phase, thus substantiating the hardening effect of EDM (54). Hyflex EDM exhibits a significantly increased cyclic fatigue resistance in comparison to Hyflex CM, M-wire based instruments, and conventional NiTi systems (19, 43, 54–57). This system also tends to create centered canal preparations, hence respecting the original root canal anatomy (49, 58, 59). Currently, there is no evidence regarding the superiority of Hyflex EDM cutting efficiency. This system is composed of three instruments used in a sequence: one for coronal (size 25,12 taper) enlargement; one for glide path (size 10,.05 taper); and last one for canal shaping. The file for canal shaping has a variable taper, 0.25 mm tip with a taper 0.08 for the initial 4 mm, which decreases to 0.04 toward the midpoint. Hyflex EDM also has different cross section designs along its length, having a quadrangular cross section at the starting

point, rectangular at the middle, and becoming triangular at the coronal part. A speed of 500 rpm with a torque of 2.5 N/cm is recommended for this system (19, 59).

Vortex Blue and Protaper Gold (Dentsply) were first introduced in 2011 as ProFile Vortex Blue. These files are manufactured through a complex heating–cooling proprietary treatment resulting in a visible titanium oxide layer on the surface, which imparts a blue colour to the alloy. They are now available as two gold and two blue heat-treated systems. Two of them are used in reciprocating motion (Reciproc Blue, VDW; WaveOne Gold), and other two are used in rotary motion (ProFile Vortex Blue; ProTaper Gold) (60). These systems can be deformed and hence also display controlled memory effect (61). They differ from CM wire systems as they are ground before they undergo the post-machining heat treatment (44). The austenite finish temperature of Vortex Blue was found to be around body temperature (38°C) whereas the martensitic start temperature is around 31°C. Despite having lower transformation temperatures, these systems contain a greater amount of stable martensite than M-wire, thus increasing the softness and ductility of the alloy (62). ProTaper Gold has a transformation temperature well above the body temperature, leading to mainly martensitic or R-phase under clinical conditions (63). The flexibility and fatigue resistance of all Blue heat-treated and Gold instruments was found to be high as compared with the conventional NiTi and M-wire instruments (56, 61–70). All Gold and Blue heat-treated systems produce well-centered canal preparations in especially severely curved canals (58, 71, 72).

Max-Wire (Martensite-Austenite-electropolish-fileX), recently introduced by FKG Dentaire, is the first endodontic file system that combines both the shape memory effect and superelasticity in a single system in clinical applications. The two available marketed instruments of Max-Wire are XP-endo Shaper and XP-endo Finisher (both FKG Dentaire). These files are relatively straight in their martensitic phase at room temperature, which changes to curved shape due to phase transformation to the austenitic phase when exposed to intracanal temperature. Hence, it possesses the shape memory effect when inserted into the canal (martensite state to austenite state) and exhibits superelasticity during canal preparation. The curved shape of these files enables them to adapt very well to canal irregularities (60). Studies have reported significantly increased cyclic fatigue resistance of XP-endo Shaper compared to Hyflex CM, Vortex Blue, and iRaCe (73, 74). However, they had less torsional resistance compared to Vortex Blue (74, 75)

2Shape File System (MicroMega) is a new generation file system produced with a proprietary heat treatment (T-wire), which aims to enhance both the flexibility and cyclic fatigue resistance by 40% in comparison to One Shape (53, 76). This system has the latest generation of cross section with triple helix, two main cutting edges, and one secondary cutting edge, which make a perfect compromise between cutting efficiency and debris removal. 2Shape rotary file system consists of two files: a TS1 (25/.04) and TS2 (25/.06) (77).

One Curve (MicroMega) is a single file NiTi rotary system introduced in 2017, based on one single file for shaping root canal (78). One Curve file system is produced with a C-wire heat

**TABLE 1.** Composition, properties, and recommended use of different NiTi systems

NiTi System	Alloy	Composition	Properties	Recommended use
Hyflex CM	CM wire	Martensite with different amounts of austenite and R-phase	<ul style="list-style-type: none"> <li>• No superelasticity</li> <li>• High resistance to cyclic fatigue</li> <li>• Increased flexibility</li> </ul>	<ul style="list-style-type: none"> <li>• Severely curved canals</li> <li>• Bypassing ledges</li> </ul>
Hyflex EDM	CM wire; EDM technology	No austenite phase	<ul style="list-style-type: none"> <li>• Increased cutting efficiency</li> <li>• Increased cyclic fatigue resistance</li> </ul>	<ul style="list-style-type: none"> <li>• Straighter canals</li> <li>• Used in combination with Hyflex CM in severely curved canals</li> </ul>
BT-RaCe	Conventional NiTi	Austenite-Electropolished	<ul style="list-style-type: none"> <li>• Triangular cross section</li> <li>• Booster tip</li> </ul>	<ul style="list-style-type: none"> <li>• Conservative instrumentation of all types of canals</li> <li>• Original canal shape maintained</li> </ul>
Vortex Blue and ProTaper Gold	M-wire	Martensite TiO <sub>2</sub> layer on surface	<ul style="list-style-type: none"> <li>• Shape memory</li> <li>• Super elasticity</li> <li>• Increased cyclic fatigue resistance</li> </ul>	<ul style="list-style-type: none"> <li>• Severely curved canals</li> <li>• Bypassing ledges</li> </ul>
XP-endo Shaper XP-endo Finisher 2Shape	Max-Wire  T-wire		<ul style="list-style-type: none"> <li>• High resistance to cyclic fatigue</li> <li>• Superelasticity</li> <li>• Shape memory</li> <li>• Asymmetric cross section</li> <li>• Additional cutting edges</li> </ul>	<ul style="list-style-type: none"> <li>• Complex root canal morphology</li> <li>• Complex root canal morphology</li> </ul>
One Curve	C wire		<ul style="list-style-type: none"> <li>• Increased flexibility</li> <li>• Better cyclic fatigue resistance</li> </ul>	<ul style="list-style-type: none"> <li>• Complex root canal morphology</li> </ul>

treatment technology. As claimed by the manufacturer, this instrument has a controlled memory and thus the ability to pre-bend, which enhances the shaping of root canal (79). The One Curve file has a variable cross section for a better centering ability and cutting efficiency (79). The cyclic fatigue resistance of One Curve file is reported to be 2.4 times higher when compared to OneShape system (80).

The composition, alloy, properties, and recommended use of these new systems are summarized in Table 1.

## CONCLUSION

With emerging technology, we see endodontics being swept away in the latest wave of technization. There is plethora of different systems available, and a large number of studies have focused on various physical and chemical aspects of NiTi files. Various proprietary methods and treatments have been introduced to enhance the cutting ability and file design. Files with the austenite phase have super elastic properties and are recommended to be used in straight or mildly curved canals, whereas those instruments composed of the martensite phase possess high flexibility along with increased resistance to cyclic fatigue and are recommended to be used while preparing canals with complex curvatures. Heat-treated and controlled memory NiTi alloys are being used widely nowadays as reflected by the current literature. These newer designs have increased flexibility and reduced shape memory property. When used clinically, these instruments can better penetrate

the entrance of the canals as they can be pre-bent to maintain the flexed shape.

While we are riding the wave, let us not forget that an experienced endodontist is the foremost formula for success, whereas the material being used is only a secondary factor. Prudent use of contemporary devices along with the basics of anatomy will lead to a predictable higher quality of root canal treatment on a broader basis, thus helping to preserve more teeth for a greater number of years.

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