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Review Article

Forging flexibility: The science and innovation behind modern NiTi rotary endodontic files

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Abstract

Nickel-titanium (NiTi) rotary instruments have revolutionized root canal therapy by offering unparalleled flexibility, superelasticity, and efficiency in canal shaping. This article reviews the metallurgical principles and proprietary innovations that have transformed conventional NiTi into a smart and adaptive material, including microstructural phase control, heat treatment protocols, surface modification techniques, and commercially available thermally modified file systems. These advancements enhance clinical performance by improving cyclic fatigue resistance, shaping efficiency, and patient safety.

Keywords: Nickel-titanium (NiTi), Alloys rotary, Endodontic instruments heat treatment, Surface modification, Superelasticity, Shape Memory, Cyclic fatigue resistance.

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1. Introduction

Endodontics is a dental specialty focused on the diagnosis and treatment of pathologies affecting the dental pulp and surrounding periapical tissues.[1] A successful root canal treatment is built upon the foundation of the endodontic triangle: proper diagnosis, detailed knowledge of root canal anatomy, and thorough debridement.[2] These three components work in harmony to ensure the effective elimination of infection and long-term tooth retention.

Because it eliminates bacteria, debris, and infected tissue from the canal system, biomechanical preparation is essential to root canal therapy.[3] Traditionally, stainless steel hand files were used, but their lack of flexibility often resulted in complications such as canal transportation, ledging, or even perforation—especially in curved or narrow canals.[1]

The introduction of nickel–titanium (NiTi) instruments marked a major advancement in endodontics due to their unique superelastic and shape memory properties, allowing them to navigate complex canal curvatures while maintaining their original shape.[4] These properties minimize the risk of iatrogenic damage and improve procedural safety.

To further enhance performance, newer NiTi alloys have been developed. M-Wire improves resistance to cyclic fatigue, while Controlled Memory (CM) wire allows pre-bending of instruments and better canal adaptability. Max Wire, used in temperature-responsive systems like XP-Endo Shaper, can expand and adapt inside the canal to enhance cleaning.[5]

Additionally, heat-treated surface modifications, such as Gold and Blue technologies, have been introduced to further increase the flexibility and fatigue resistance of NiTi instruments. These advancements provide clinicians with tools that combine strength, adaptability, and efficiency—leading to safer and more predictable outcomes.[5]

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This article focuses on reviewing recent developments in the design and metallurgy of NiTi rotary file systems, emphasizing their role in improving clinical outcomes in endodontics.

2. Metallurgy of NiTi

2.1. Composition of NiTi alloys

Often referred to as 55 Nitinol, NiTi is a binary alloy made up of roughly 55 weight percent nickel and 45 weight percent titanium. This composition is equiatomic (1:1 atomic ratio), which gives the alloy its unique superelasticity and shape memory properties, ideal for endodontic instruments. Some variants may include up to 2 wt% Cobalt to improve flexibility, fatigue resistance, and control over transformation temperatures, enhancing clinical performance.[6]

2.1.1. Microstructural phases

Transitions between the various crystallographic phases that make up equiatomic NiTi alloys significantly influence the alloy's mechanical behavior:[6,7,17,18]

2.2. Austenite phase

2.2.1. Stability

Austenite is the parent phase of NiTi, stable at higher temperatures and in the absence of stress. It represents the default structure of the alloy at room temperature or during clinical use when heat from the body is present.

2.2.2. Mechanical properties

In this phase, NiTi exhibits high stiffness and superelastic behavior, meaning the alloy can undergo significant deformation under stress but immediately returns to its original shape once the stress is removed. It has a high restoring force, making it ideal for cutting efficiency but less adaptable in complex canal morphologies.

2.2.3. Clinical significance

1. Best suited for straight or moderately curved canals due to its rigidity.
2. The high recovery force ensures excellent cutting efficiency and canal shaping ability.
3. However, its lower flexibility makes it less forgiving in severely curved canals, increasing the risk of procedural errors like canal transportation or ledging.

2.2.4. Examples of rotary files in austenite phase

1. TruNatomy (Dentsply Sirona): Known for minimal invasiveness and conservative dentin removal while maintaining stiffness.
2. EdgeFile X7 (EdgeEndo): Offers high cutting efficiency and is manufactured with Fire-Wire NiTi technology, staying mostly in austenitic phase during use.

2.3. Martensite phase

2.3.1. Stability

The martensitic phase is a low-temperature phase of nickel-titanium alloy (NiTi).It can also form under stress (stress-induced transformation), which means it is present when the file is deformed during clinical use in curved canals.

2.3.2. Mechanical properties

Soft and ductile compared to the austenite phase.Highly flexible and can be bent manually before insertion (pre-bent).Once the external force is removed, it can return to its original shape, but in the canal, it adapts to the anatomy, reducing excessive restoring forces.

2.3.3. Clinical significance

1. Negotiating complex anatomies: Excellent for S-shaped or severely curved canals where flexibility is crucial.
2. Pre-bending capability: Allows clinicians to pre-bend the file tip to bypass calcifications or ledges.
3. Reduced canal transportation: The high flexibility allows the instrument to follow the original canal path more closely, preserving dentin.
4. Decreased fracture risk: Because it is more flexible, cyclic fatigue resistance is improved, lowering the risk of unexpected separation.

2.3.4. Examples of files utilizing martensitic phase

1. HyFlex CM (Coltene): Controlled Memory (CM) wire technology, which remains in martensitic form at body temperature, offering exceptional flexibility and reshaping ability after deformation.
2. XP-endo Shaper (FKG Dentaire): Uses a proprietary alloy that is martensitic at room temperature and transforms to a more active shape inside the canal (adaptive shaping), allowing it to expand and adapt to irregular canal spaces.

2.4. R-Phase (Rhombohedral intermediate phase)

2.4.1. Stability

1. The R-phase is a transitional (intermediate) phase between the austenite (high-temperature, superelastic) and martensite (low-temperature, flexible) phases.
2. It forms during the phase transformation process and is generally stable over a narrow temperature range.

2.4.2. Mechanical properties

1. More flexible than the austenitic phase but not as ductile as martensite.
2. Exhibits a narrow transformation hysteresis, meaning it changes phases with less temperature fluctuation, making its behavior more predictable.
3. Improved cyclic fatigue resistance, which helps reduce the chance of instrument fracture when rotating in curved canals.

2.4.3. Clinical significance

1. Good for moderately curved canals: Offers sufficient flexibility to negotiate moderate curves without excessive deformation.
2. Balanced performance: Provides an ideal mix of cutting efficiency (from the austenite phase) and flexibility (from the R-phase), helping maintain efficient shaping while reducing canal transportation.
3. Enhanced durability: The improved resistance to cyclic fatigue extends the lifespan of the instrument, making it safer and more reliable in clinical practice.

2.4.4. Examples of files utilizing r-phase

1. Twisted File (SybronEndo): Produced using a proprietary twisting process instead of traditional grinding, and heat treatment to enhance R-phase properties for better flexibility and strength.
2. TF Adaptive (SybronEndo): Combines R-phase properties with adaptive motion technology (switches between continuous rotation and reciprocation), optimizing safety and shaping ability.

2.5. Functional properties

The two most clinically significant properties of NiTi alloys, which arise due to reversible phase transformations, are:

2.5.1. Shape memory effect[8]

1. Occurs due to heat-induced transformation between martensite and austenite.
2. After deformation in the martensitic phase, the alloy returns to its original shape upon heating above a critical transformation temperature.
3. This allows instruments to "remember" their original shape, enabling enhanced access in curved canals.

2.5.2. Superelasticity[6]

1. Occurs due to stress-induced transformation from austenite to martensite and back on unloading.
2. Enables large strains (up to 8%) to be recovered elastically.
3. Enhances the ability of NiTi files to negotiate curved root canals without permanent deformation.

2.6. Evolution of NiTi (**Figure 1**)

1. Despite the advantages provided by the superelasicity of NiTi alloy, instrument fracture is still a clinical concern. (**Table 1**)
2. Thus, thermomechanical processing aims to improve the mechanical properties and behaviour of NiTi alloys.[8]

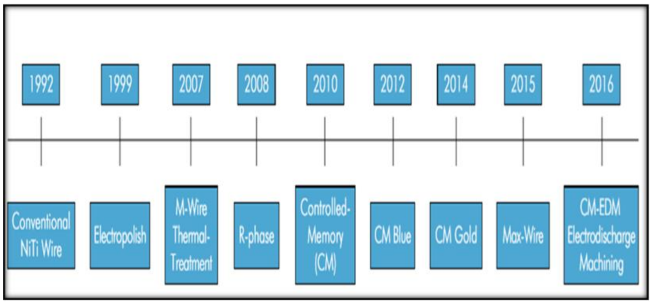

Figure 1: Evoluation of nickel titanium

Table 1: Generational classification of niti rotary instruments[9]

Generation	Key Innovations	Examples
1st Generation (1992–1995)	Fixed taper (0.04–0.06); Passive radial lands; Large number of instruments	ProFile Series 29, LightSpeed, Quantec, GT Rotary
2nd Generation (2001 onward)	Active cutting edges; No radial lands; Reduced file sequence; Some with electropolishing	ProTaper, EndoSequence, BioRaCe
3rd Generation (2007 onward)	Heat-treated alloys for improved flexibility & cyclic fatigue resistance	Vortex Blue, Twisted File, HyFlex CM, K3XF
4th Generation	Reciprocating motion; Single-file systems; Self-adjusting file (SAF) introduced	WaveOne, Reciproc, SAF
5th Generation	Offset center of mass/rotation; Wave motion for better debris removal and reduced engagement	Revo-S, One Shape, ProTaper Next
6th Generation	Task-specific instruments; Glide path preparation and retreatment files	ProGlider, XP Finisher, ProTaper Retreatment Kit
7th Generation	New manufacturing techniques: Twisting, EDM, Shape-setting	Twisted File, XP Shaper, TRUShape, SAF

2.7. Strategies in the alteration of NiTi alloy

The performance of nickel–titanium (NiTi) rotary instruments has been significantly enhanced in recent years through various strategic modifications aimed at overcoming challenges such as instrument fracture, fatigue failure, and poor adaptability in curved canals. These advancements are broadly classified into surface modifications and microstructural or thermomechanical treatments, each contributing to the improved reliability, safety, and efficiency of endodontic instrumentation.

2.7.1. Surface modification strategies [7]

2.7.1.1. Plasma immersion ion implantation (PIII)

By using plasma to inject nitrogen ions into the NiTi surface, Plasma Immersion Ion Implantation (PIII) increases hardness and decreases defects. Clinically, it increases cutting efficiency and resistance to cyclic fatigue, making files more robust and appropriate for curved canals. Gavini et al. demonstrated that nitrogen ion implantation enhanced the NiTi rotary instruments' resistance to cyclic fatigue. According to Rapisarda et al., ionic implantation improved wear resistance, enhanced cutting efficiency, and revealed variations in surface characteristics.

2.7.1.2. Titanium oxide coating

Titanium is known to have a greater affinity for oxygen than Nickel. As a result, the oxide generated at moderate temperatures with longer exposure times is mostly made up of TiO_2, which forms and grows slowly. The impact of the TiO_2 layer on the mechanical properties of endodontic instruments and their ability to withstand corrosion in NaOCl solution were investigated by Aun DP et al. and they discovered that NaOCl has a strong corrosion resistance and an increase in cutting efficiency. After corrosion, the coated instruments performed better in terms of fatigue life. They came to the conclusion that since the TiO_2 layer can withstand comparatively large deformations, this property ought to be preserved for the strained samples. Therefore, it has been demonstrated that using the dip-coating sol-gel technique to coat endodontic instruments with a flexible TiO_2 protective layer enhances their cutting efficiency, corrosion behavior, and fatigue resistance.

2.7.1.3. Thermal nitridation

Thermal Nitridation (PIRAC Technique) introduces nitrogen into NiTi at ~250°C, forming a TiN outer layer and Ti_2Ni sublayer. This improves corrosion resistance in NaOCl. Clinically, it enhances durability, but precise temperature control is crucial to preserve flexibility and superelasticity.

2.7.1.4. Cryogenic treatment

The wear, abrasion, corrosion resistance, microhardness, and strength of metals have all been enhanced by deep dry cryogenic techniques. Without altering the alloy's elemental crystalline composition, it has been observed to impact the instrument's whole cross section as opposed to just its surface. It entails hanging the metal over a liquid N-filled super-cooled bath and letting it gradually warm up to room temperature. Kim et al. reported that the microhardness of cryogenically treated instruments was noticeably higher. According to Vinothkumar et al., CT considerably improved the cutting efficiency of NiTi instruments, but it had no effect on wear resistance. According to George et al., CT considerably increased the NiTi rotary files' resistance to cyclic fatigue.

2.7.1.5. Electropolishing

Electropolishing is a final-stage surface finishing process that removes microscopic irregularities from NiTi files. Clinically, it reduces stress concentration, enhancing resistance to torsional and flexural fatigue, though its effectiveness may vary with file design and usage.

2.7.2. Metallurgical modifications of NiTi files

2.7.2.1. Conventional NiTi alloy

Conventional nickel-titanium (NiTi) rotary files are mainly in the austenitic phase at room temperature, making them stiff and superelastic. While they can transform to stress-induced martensite under stress to allow some flexibility, they tend to revert to their original shape once the stress is released. This increases the risk of canal transportation, ledging, and potential perforation, especially in curved or complex canals.

Additionally, these files are usually produced using a grinding process, which introduces surface defects like micro-cracks and irregularities. These flaws act as weak points, reducing resistance to cyclic fatigue and making the files more prone to unexpected separation during clinical use.[8,19] Example: RaCe (**Figure 2**)

Figure 2: Conventional NiTi alloy files

2.7.2.2. Thermomechanical treatment of NiTi

This process combines mechanical deformation (such as twisting, forging) and heat treatments (like quenching and annealing) to modify the crystalline structure of nickel-titanium (NiTi) alloys. By increasing the content of martensitic or R-phase structures, these treatments significantly improve the file's flexibility and resistance to cyclic fatigue. Clinically, these enhancements allow instruments to better adapt to severe canal curvatures, reducing the risk of transportation, ledging, and file separation.[10,19]

Examples include WaveOne (Dentsply) and TruNatomy (Dentsply Sirona)**,** which utilize proprietary heat-treated NiTi alloys to achieve higher flexibility and safety. Other systems, such as HyFlex CM (Coltene) and ProTaper Gold (Dentsply Sirona)**,** also use specialized thermomechanical processing to improve performance, increase cyclic fatigue resistance, and provide greater control during root canal shaping. (**Figure 3**)

Figure 3: Thermo mechanical treatment NiTi file

2.7.2.3. Heat treatment of NiTi alloys

Heat treatment alters the phase transformation behavior of NiTi alloys by modifying the austenite finish temperature (Af). This adjustment increases the proportion of martensitic or R-phase structures at clinical temperatures, improving flexibility, cyclic fatigue resistance, and canal adaptability. Clinically, heat-treated files are safer in complex and curved canals, reduce the risk of canal transportation, and can be pre-bent to navigate calcified or highly curved anatomies. Additionally, they show enhanced resistance to separation, contributing to better overall treatment success and fewer complications.[11]

Examples include RECIPROC Blue (VDW) and XP-endo Shaper (FKG Dentaire), both of which employ proprietary heat treatments to achieve these improved properties. (**Figure 4**)

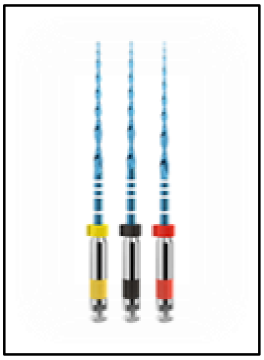

Figure 4: Heat treatment niti file

2.7.2.4. M-Wire

M-Wire is a thermomechanically treated nickel-titanium (NiTi) alloy designed to increase martensitic content, which improves flexibility and cyclic fatigue resistance compared to conventional NiTi. The enhanced flexibility allows instruments to better follow curved or complex canal anatomies, while the improved fatigue resistance reduces the likelihood of unexpected file separation. Clinically, these advantages make M-Wire files safer and more effective for shaping challenging canals.[10]

Examples: ProFile GT Series X, ProTaper Next, WaveOne, and PathFile (all from Dentsply Sirona). (**Figure 5**)

Figure 5: M-Wire rotary file

2.7.2.5. Controlled memory (CM) wire

CM Wire is a heat-treated nickel-titanium (NiTi) alloy designed to stay predominantly in the martensitic phase at body temperature (austenite finish temperature, Af ≈ 50°C). This gives it high flexibility**,** excellent adaptability, and no shape memory effect, allowing it to maintain its bent shape when needed. Clinically, it can be pre-bent to navigate highly curved or calcified canals, reducing the risk of canal transportation, ledging, and procedural errors. The increased flexibility also enhances cyclic fatigue resistance, making these instruments safer and more durable.[10]

Examples**:** HyFlex CM (Coltene), Typhoon CM (Clinician's Choice), and EdgeFile CM (EdgeEndo). (**Figure 6**)

Figure 6: CM wire rotary file

2.7.2.6. Gold and blue wire

These alloys undergo advanced post-machining heat treatments, which modify the austenite finish temperature (Af) and improve phase transformation behavior. By increasing martensitic or R-phase content, these treatments significantly enhance cyclic fatigue resistance and flexibility, making the files more adaptable and safer in curved or complex canals. Clinically, they provide better control, reduce the risk of file separation, and help preserve canal anatomy.[12]

Examples: ProTaper Gold and WaveOne Gold (gold heat-treated wire), and RECIPROC Blue (blue heat-treated wire), all of which use proprietary coloring and thermal processing to indicate their enhanced metallurgical properties.

2.7.2.7. R-Phase NiTi

R-phase NiTi is created by heat-treating conventional NiTi to induce a rhombohedral intermediate structure**,** positioned between austenite and martensite phases. This modification results in improved flexibility, lower elastic modulus**,** and moderate shape memory, allowing the files to adapt better to canal curvatures while still returning to shape when needed.

Clinically, the R-phase enables the twisting process during manufacturing (instead of traditional grinding), which enhances the instrument's strength, reduces surface defects, and improves resistance to cyclic fatigue. This ultimately leads to safer and more efficient canal shaping.

Examples: Twisted Files (SybronEndo) and K3XF (Kerr). (**Figure 7**)

Figure 7: R-Phase rotary file

2.7.2.8. MaxWire technology

MaxWire is a specially heat-treated nickel-titanium (NiTi) alloy designed to be in the martensitic phase at room temperature**,** giving it excellent flexibility and the ability to be pre-bent during insertion. Once introduced into the canal and warmed to body temperature, it transforms into the austenitic phase, allowing the file to expand and adapt to the canal's natural shape for thorough cleaning and shaping.

This unique phase-changing behavior combines high flexibility on insertion with strong shaping and cleaning capability once activated inside the canal, minimizing the risk of canal transportation and improving debridement of irregularities.[12]

Examples: XP-endo Shaper and XP-endo Finisher (FKG Dentaire).

2.7.2.9. EDM technology (Electrical discharge machining)

Electrical discharge machining (EDM) is a non-contact thermal erosion process that removes metal from nickel-titanium (NiTi) instruments using precisely controlled electrical discharges. This method creates a cratered, rough surface**,** which increases the surface area and enhances mechanical interlocking with dentin debris during shaping.

The unique surface texture produced by EDM significantly improves the file’s cyclic fatigue resistance and overall fracture resistance, making these instruments especially safe and effective in curved or complex canals. EDM is often combined with heat treatment to further optimize flexibility and durability.[13](**Figure 8**)

Example: HyFlex EDM (Coltène).

Figure 8: Hyflex edm (Coltène)

2.7.2.10. SAF – self-adjusting file system

The Self-Adjusting File (SAF) is an innovative nickel-titanium (NiTi) instrument designed with a thin-walled, hollow, compressible lattice structure**.** It stays entirely in the austenitic phase at body temperature**,** yet its flexible design allows it to adapt three-dimensionally to the canal shape without relying on phase transformation. Instead of rotating, it operates using a vibratory (in-and-out) motion**,** combined with continuous irrigation. This unique mechanism allows the SAF to remove dentin by abrasion rather than cutting**,** offering a gentler and more conservative approach.

Clinically, the SAF is especially effective in oval or irregularly shaped canals**,** where it reduces the risk of canal transportation and helps maintain original anatomy. Additionally, its design allows for simultaneous shaping and irrigation**,** improving cleaning efficiency and overall treatment outcomes.[14]

Example: SAF System (ReDent Nova, Israel).

2.8. Research evidence on NiTi metallurgy

1. Kasuga *et al.* compared five heat-treated NiTi files (HyFlex EDM, HyFlex CM, Vortex Blue, RE file CT, JIZAI) with a non-heat-treated Mtwo, all size #40/0.04. Heat-treated files showed greater flexibility and cyclic fatigue resistance at room temperature, with EDM

performing best. However, at body temperature, this advantage was reduced—especially for files with mixed martensite/R-phase and austenite—highlighting the need for testing under clinical temperature conditions.[15]

2. Alsofi *et al.* compared EndoSequence Reciprocating System (ESR), WaveOne Gold (WOG), and Reciproc Blue (RB) heat-treated nickel-titanium (NiTi) files. EndoSequence Reciprocating System had the highest austenite finish temperature (Af) and best cyclic fatigue resistance in dynamic tests, showing that heat-treatment protocols affect clinical performance and durability.[16]
3. Kang *et al.* compared the mechanical properties of five heat-treated nickel-titanium (NiTi) file systems—OneShape Pro (OSP), Vortex Blue (VB), One Curve (OC), TruNatomy Prime (TN), and HyFlex CM (HCM)—designed for minimally invasive instrumentation. Tests included torsional resistance, bending stiffness, and cyclic fatigue resistance. HyFlex CM had the lowest bending stiffness, while Vortex Blue showed the highest cyclic fatigue resistance. Results indicate that variations in heat treatment and design significantly influence flexibility and fracture resistance, which are critical for safe canal shaping.[17]

3. Discussion

Recent innovations in NiTi file design and metallurgy have significantly improved endodontic outcomes. Heat-treated alloys like CM Wire, Gold Wire, and Blue Wire enhance fatigue resistance, making them safer in curved canals. Phase transformation tuning allows manufacturers to control the balance between flexibility and stiffness, improving file performance in varying anatomies. Cryogenic processing enhances durability by refining the alloy's microstructure. MaxWire technology enables temperature-driven adaptability, making it highly effective in minimally invasive and anatomically complex canals. Electropolished surfaces reduce surface defects, lowering the risk of file fracture during repeated use. Single-file reciprocation systems, such as WaveOne and RECIPROC, offer faster preparation with fewer procedural errors, improving efficiency and safety in clinical practice.[18,19]

4. Conclusion

Advancements in the metallurgy and design of nickel-titanium (NiTi) rotary endodontic files have significantly enhanced the safety, efficiency, and predictability of root canal treatment. Innovations such as proprietary heat treatments, controlled phase transformations (including martensite and R-phase optimization), surface modifications, and adaptive technologies like MaxWire and Self-Adjusting File (SAF) systems have greatly improved file flexibility, cyclic fatigue resistance, and canal adaptability. These technological breakthroughs not only increase instrument longevity but also improve clinical outcomes by minimizing procedural errors, preserving original canal anatomy, and reducing the risk of instrument separation.

5. Source of Funding

None.

6. Conflict of Interest

None.

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