An Overview of the Mechanical Properties of the Orthodontic Wires: A Review

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ABSTRACT

Introduction: This review aimed to provide theoretical support, based on orthodontics and mechanical engineering concepts, to emphasize the applicability and the mechanical properties involved in stainless steel, cobalt chromium, titanium-molybdenum and titanium based alloys for specialists in this field.

Materials and Methods: The search strategy for articles selection was focused on PubMed and Scopus from 1963 to 2024.

Results: A total of 501 citations were identified by Medline (through PubMed) and 478 by Scopus. A total of 68 articles were considered eligible for describing the basic mechanical properties of alloys and thermal tests, and tests to examine the strength of materials and the surface of the material or its cyistallography.

Conclusion: Metallic alloys contain specific characteristics, such as resilience, rigidity, stored energy, formability, low friction surface, low cost and biocompatibility. Stainless Steel (SS) wires have the advantage of low cost and good corrosion resistance, good resilience and good formability. Cobalt-chromium and nickel-chromium have characteristics very close to SS wires but are expensive. Titanium-molybdenum alloys revealed springback superior than SS wires, good formability and high friction coefficient. Nickel-titanium based wires present poor formability, high friction coefficient, even though some of them present the shape memory effect and superelasticity. Ti-Nb(niobium) and Timolium present intermediate properties in relation to SS and TMA wires. Aesthetic alloys are fragile to fracture and relaxation fatigue over time and are dependent on moisture absorption and temperature changes. The properties of metallic wires are function of wire composition, variables during machining process and heat treatment.

Keywords: Aesthetic wires; Cobalt-chromium; Mechanical Properties; Metallic wires; Nickel-titanium; Stainless steel; Titanium-molybdenum

INTRODUCTION

Alloys used in orthodontics undergo specific thermo-mechanical processes that have unique mechanical, thermal and electrical properties. The manufacturing process is responsible for the characteristics of each alloy. In addition to new techniques, i.e., the straightwire, such as the advent of the simplification of wires use, and the superelastic and shape memory wires and the knowledge of self-ligating brackets, the physical characteristics of the archwires are important

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to master. The mechanical properties are important to characterize the metallic alloys. Such properties can be verified in the elastic phase, because it is in this phase that the deflection of the archwires are obtained. The knowledge of the plastic phase of the alloys is also important, because, in certain clinical situations, the orthodontic archwires can suffer bending until to surpass the elastic limit. As examples of the elastic properties we have, the elastic limit of proportionality (σp), the yield limit or yield stress (σy, YS), the modulus of elasticity (E), and the resilience, which is measured by the module of resilience (Ur).[1-8] Fig. 1 shows a illustration of these properties. Metal alloys sometimes have the same crystal structures, differing only in the atoms that compose them. Other times they differ in terms of the internal angulations of the crystal lattice and in the size of the unit cell itself (lattice parameters), or even in the position that the atoms occupy within the unit cell, characterizing different crystal structures. Table 1 shows metals used in orthodontics and their mechanical properties. The current scenario shows that traditional alloys such as stainless steel, chromium-cobalt, titanium-molybdenum, and superelastic alloys have been intensively tested and continue to be used in daily clinical practice. Regarding aesthetic alloys, there has been a decline in demand due to problems such as polymeric coatings that broke easily that is delamination, loss of viscoelastic properties, and discoloration. The introduction of aligners some years ago also contributed to this issue; however, metal alloys can be used as auxiliary means in hybrid mechanics along with aligners.

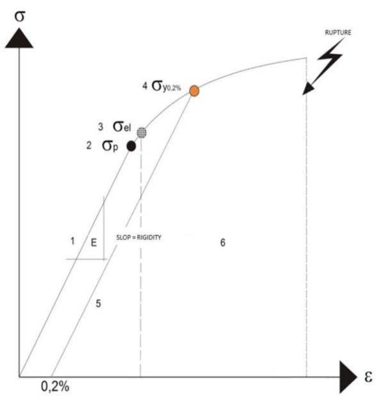

Fig. 1: Stress-strain diagram. The angular coefficient or slop denotes the curve inclination that indicates the E for a wire. 1. Modulus of elasticity (E); 2. Elastic limit of proportionality (σp); 3. Elastic limit (very close to σp); 4. Yield limit or yield stress (σy, YS) tolerance of 0.2% is accepted; 5. Slop; 6. Resilience, which is measured by the module of resilience (stored energy Ur).

Table 1. Wire material and mechanical properties

Wire Material	Elastic Limit (MPa)	Modulus of Elasticity E (GPa)
Stainless Steel	1720/1543-1966	193
Titanium Molybdenum	1240-1380/769-1254	65-100
Cobalt-Chromium	1792	193
Nickel Titanium	1650	33

This study aims to present a review of the mechanical properties of wires commonly used in orthodontics.

MATERIALS AND METHOD

Search Strategy

The electronic databases Medline (through PubMed) and Scopus were searched. All articles were published in English. The articles were published between January 1963 and May 2024 and the keywords used were "Orthodontics and Tension tests; Orthodontics and three-point tests; Orthodontics and torsion tests". Keywords "shape-memory effects" were searched in Scopus data base. "NiTi crystallographic transformation"was also searched in Scopus database.

Eligibility criteria:

Eligibility and potential articles were determined by applying the following criteria: Inclusion criteria: articles that contained information on tensile (traction) tests, three-point tests and torsion tests, resistivity or other methods that verify the mechanical behavior, the alloy surface characteristic, the material strength and crystallography of metal alloys used in orthodontics, i.e., tests with scanning electronique microscopy (SEM), differential scanning calorimetry (DSC), temperature modulated differential scanning calorimetry (TMDSC), X-ray diffraction (XRD) techniques, X-ray fluorescence (XRF), dynamic-mechanical thermal analysis (DMTA), were accepted. Two revision articles[2,12] and seven articles[31-37] considering crystallographic changes in NiTi alloys were selected from journals dealing with materials science in order to better support the understanding of crystallographic changes in these alloys.

Exclusion criteria:

Articles related to cell biology and orthodontic archwires, grey literature, microbial interface and archwires, archwires and adhesives, archwires and brackets, coil springs, closing loops, clinical cases, surface roughness tests, retrospective and prospective studies with patients, and randomized clinical trials with patients and orthodontic archwires were excluded. (see Flow Chart in Fig. 2).

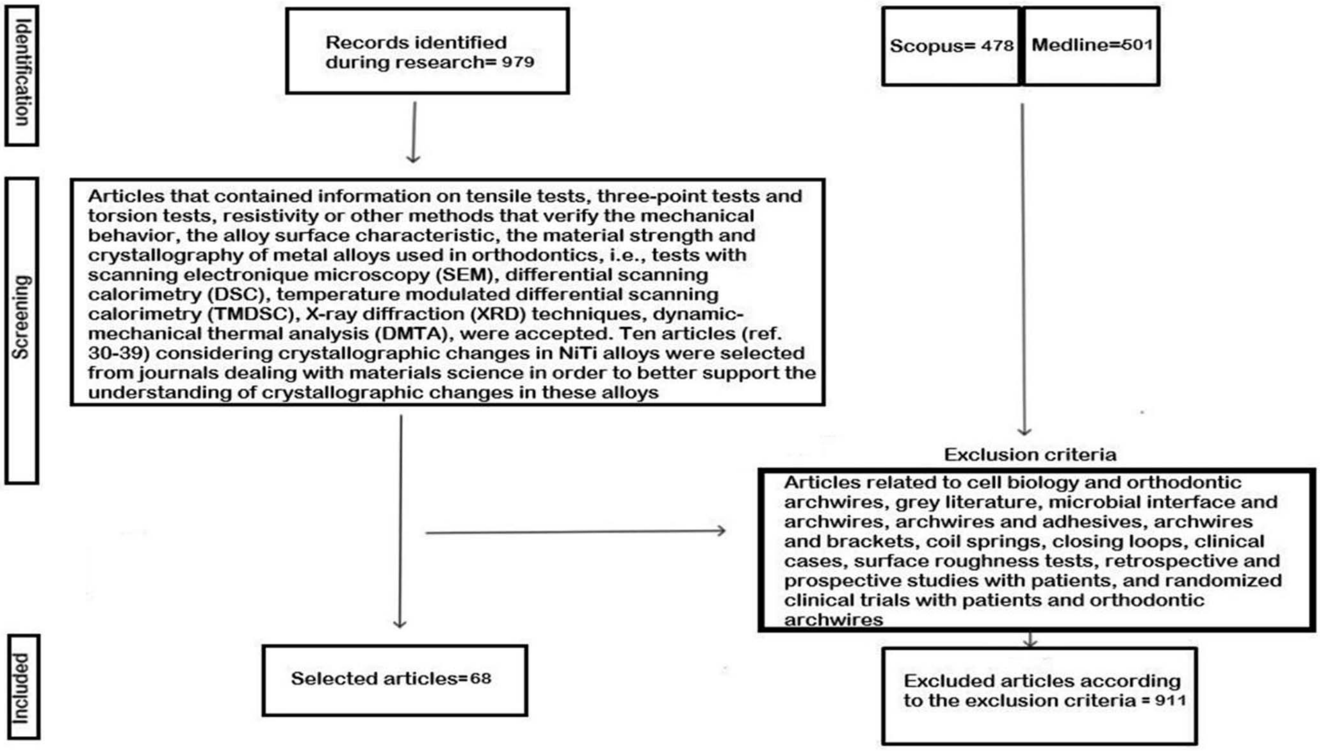

Fig. 2: Flow chart.

Table 2. Summary including authors, wire material, findings,method and journal.

Authors	Wire Material	Method	Findings	Journal
Buehler and Gilgfrich (1963)	Nitinol	Bending tests	Alloys close to the stoichiometric composition of TiNi transform into the correlated phases and when cooled.	J Appl Phys
Ingerslev (1966)	Stainless Steel 18/8	Heat Treatment	Controlled heating of steel after severe bending removes internal stresses	Angle Orthod
Andreasen and Hilleman (1971)	Nitinol	Bending and traction tests	Nitinol (0.019") vs stainless steel (solid and braided), it was observed that the heat-treated Nitinol exhibited comparable or superior strength at certain deformations, with the advantage of returning to its original shape	J Am Dent Assoc
Burstone and Goldberg (1980)	Gold, Stainless Steel, Ti-Molybdenum and NiTi wires.	Revision Article	Good springback, Good formability and accepts welding	Am J Orthod
Drake et al. (1982)	Stainless Steel, Ti-Molybdenum and NiTi wires.	Bending, Traction and Torsion Tests	Beta titanium alloys exhibit better springback than steel alloys.	Am J Orthod Dentofacial Orthop

Watanabe et al. (1982)	NiTi	Tensile and Bending tests	Superelastic NiTi orthodontic wire exhibits a constant stress plateau (2% to 5%) and low permanent deformation	Shika Rokog Zass
Kusy and Dilley (1984)	Stainless Steel, Ti-Molybdenum and NiTi wires.	Bending tests	B-Ti wires exhibit approximately 40% of the stiffness of stainless steel, while maintaining good formability.	Am J Orthod
Donovan et al. (1984)	Beta-titanium	Tensile-shear, tensile-torsional, and cold bending (90o) tests to evaluate weldability.	Reduction of ductility in regions close to the weld	Am J Orthod
Burstone, Qin and Morton (1985)	Chinese NiTi	Bending tests	Chinese NiTi has extremely low flexural stiffness and a high springback making it ideal for the initial stages of leveling.	Am J Orthod
Miura et al. (1986)	Japanese NiTi	Three-point bending tests	Japanese wires presents superelasticity and the ability to release constant and light forces.	Am J Orthod
Asgharnia and Brantley (1986)	Stainless Steel, Cobalt-Chromium, Ti-Molybdenum and NiTi wires.	ADA n.32 specification. Conventional bending and torsion tests	Stainless steel and Elgiloy show greater rigidity, enhanced by heat treatment, while NiTi and TMA alloys have greater flexibility, with heat treatment significantly increasing the YS of the wires.	Am J Orthod Dentofacial Orthop
Khier et al. (1988)	Stainless Steel "as received" and heat-treated	X-ray diffraction (XRD) and bending and traction tests	Cold working increases internal stress. Heat treatment reduces internal stresses, minimizing the risk of fracture.	Am J Orthod Dentofacial Orthop
Kapila and Sachdeva (1989)	Stainless Steel, Cobalt-Chromium, Ti-Molybdenum, NiTi and Co-axial wires	Revision article	Stainless steel for finishing (high stiffness), NiTi for alignment (high springback), TMA for closing mechanics (medium stiffness), and Co-Cr for bending due to the ductility.	Am J Orthod Dentofacial Orthop
Elias et al.(1993)	Stainless Steel	Ferromagnetic resonance (FMR)	Proper heat-treatment significantly increases the YS. Heat treatment should be conducted near 623 K for a period of not much less than 30 min.	J. Mater Res
Yoneyama et al. (1993)	NiTiCu	Three-piont tests cantilever-bending tests,stress-strain behavior, DSC, XRD, SEM and Fastening tests	Light and continuous force (stable deactivation plateau) during bending, with properties dependent on the phase transformation temperature.	J Biomed Mater Res

Klump et al. (1994)	Stainless Steel, Cobalt-Chromium, Ti-Molybdenum and NiTi wires.	Traction tests.	Stainless steel and cobalt-chromium wires have greater stiffness, while titanium-molybdenum (TMA) and nickel-titanium (NiTi) wires produces superior elastic energy ratios with lighter and more constant forces.	Am J Orthod DentoFacial Orthop
Thayer et al. (1995)	Nitinol	XRD	Demonstrated via XRD that superelastic Nitinol wires undergo an austenitic to martensitic phase transformation under 6% stress, with the degree of superelasticity positively correlated to the transformation rate. The results indicated that industrial cold work negatively affects superelastic capacity. There is a large variability in between different commercial brands.	Am J Orthod DentoFacial Orthop
Bradley et al. (1996)	NiTi	DSC	Variations in the enthalpy of transformation. R phase formation during cooling.	Am J Orthod DentoFacial Orthop
Filleul et al. (1997)	NiTi, Copper NiTi (CuNiTi)	Torsion tests, differential scanning calorimetry (DSC)	CuNiTi alloys exhibit temperature-dependent stiffness, while conventional NiTi shows a more constant torque under thermal variations. The study highlighted that shape memory and the slope of the deactivation plateau are strongly influenced by thermal control.	J Phys IV
Guénin (1997)	NiTi	Testes de flexão, differential scanning calorimetry (DSC)	NiTi exhibits a reversible R-phase transformation (B2→R→B19’). The research concluded that mechanical deformations alter the material’s stability, resulting in shifts in phase transformation temperatures and increasing the hysteresis area.	J Phys III
Uchil et al. (1998)	Nitinol	Electrical resistivity tests and thermal analysis by Differential Scanning Calorimetry (DSC).	Electrical resistivity and differential scanning calorimetry (DSC) are effective methods for identifying phase transition temperatures in Nitinol.	Mater Sci Eng

Meling and Odegaard (1998)	Superelastic NiTi, NiTi "work-hardened"; braided NiTi and titanium-molybdenum	Torsion tests at 25o and 37oC.	NiTi "superelastic" materials do not always maintain constant forces, but the force/deflection behavior is variable, influenced by temperature. TMA under torsion at 37 °C, have low torsional stiffness.	Angle Orthod
Otsuka and Ren(1999)	NiTi	DSC, three-point tests, traction tests, cantilever-bending tests, XRD, SEM and dilatometry.	Nickel-rich Ni-Ti alloys (e.g.,50.7 at% Ni) aged exhibit a complex martensitic transformation, evolving from two to three transformation peaks upon cooling (2–3–2 behavior). This involves the sequence (B2→R→B19'). (Austenite-R-phase-Martensite).	Mater Sci Eng
Imai et al. (1999)	Esthetic fiber-reinforced plastic (FRP) wire, featuring a polymethyl methacrylate (PMMA) matrix reinforced with biocompatible glass fibers	Three-point tests	The results indicated that these 0.5 mm FRP (Fiber Reinforced Plastic) wires can cover the strength range required for orthodontic treatments, varying from initial nickel-titanium wires to final cobalt-chromium wires.	Am J Orthod DentoFacial Orthop
Nakano et al. (1999)	NiTi	Three-point tests	The new Japanese NiTi wire possesses superior superelasticity, maintaining an ideal constant force for tooth movement.	Am J Orthod DentoFacial Orthop
Filleul and Constant (1999)	NiTi	Torsion tests	NiTi wires exhibit superelasticity when subjected to torsion, demonstrating a deactivation "plateau." The torsional behavior was influenced by the crystalline structure which is altered by temperature, affecting stiffness and superelasticity. Although NiTi alloys demonstrate superelasticity, continuously applied torsion in rectangular NiTi wires does not necessarily provide the ideal constant moments expected for third-order torque control Different brands and compositions of NiTi wires (e.g., conventional, copper-NiTi) exhibited distinct torsional behaviors, which are essential for clinical selection.	Mater Sci Eng

Santoro et al. (2000)	Superelastic NiTi; Copper NiTi 27oC; Copper NiTi 35oC and Copper NiTi 40oC	Bending tests, electrical resistivity in controlled temperature range (between 4oC and 60oC)	Deflection caused a shift in the TTR to higher values (making them more resistant to deactivation), a phenomenon related to tension. The 27°C Copper Ni-Ti and the Heat-Activated Nitinol (3M-Unitek) were considered the most suitable for the alignment and leveling phase, as they exhibited constant superelasticity characteristics in the oral temperature range. The Copper NiTi wires (27°C, 35°C, 40°C) demonstrated better definition of the TTR due to the Cu. The 27°C Copper Ni-Ti wire maintained an excellent ability to provide constant and light force, superior to other CuNiTi wires, that required more heat to activate their superelasticity.	Am J Orthod Dentofacial Orthop
Biasi et al.(2000)	Stainless Steel	Heat treatment	Austenitic stainless steel (such as 302/304) under phase transformation (austenite to deformation-induced martensite) during cold working. The ideal temperature for heat treatment was about 450°C, to relieve internal stresses generated by cold working.	Mat. Res
Fallis et al. (2000)	photo-pultruded composite archwires (reinforcing fibers and a polymer matrix)	XRD, SEM, Three-point tests Light microscopy,	Glass fibers and polymer matrices (Photopultrusion) wires exhibit superior tensile moduli with higher flexural strength, placing them in ranges comparable to beta-titanium wires.	J Mater Sci Mater Med
Gurgel et al. (2001) a	NiTi	Torsion tests	Although superelastic NiTi wires exhibit different strength levels in bending tests, they are less effective at controlling torque (3rd order) compared to stainless steel.	Am J Orthod Dentofacial Orthop
Gurgel et al. (2001) b	NiTi	Bending and Torsion tests	Unlike bending, most superelastic NiTi wires do not exhibit a constant force plateau in torsion, failing to provide ideal moments for torque control at the start of treatment.	Am J Orthod Dentofacial Orthop

Meling and Odegaard (2001)	NiTi	Bending tests	Effect of Cold at 10°C: reduces the force exerted, and they continue to release forces below the ideal (sub-baseline) even after the oral temperature returns to normal. Effect of Heat at 80°C: increase in force, but this effect is transient. Conventional vs. Superelastic: Conventional NiTi was minimally affected, while superelastic NiTi showed high sensitivity to these thermal changes.	Am J Orthod DentoFacial Orthop
Kusy et al. (2001)	Cobalt-Chromium	Bending and traction tests	The flexibility and resilience of Cobalt-Chromium (Elgiloy) in the "as received" state are variable and independent of tempering (soft or blue, ductile or yellow, semi-resilient or green, resilient or red). In bending and tensile tests these wires are very stiff for certain phases of treatment, exhibiting superior stiffness compared to TMA and NiTi wires.	Am J Orthod DentoFacial Orthop
Iijima et al. (2002)	NiTi	Three point tests, DSC,micro-XRD,	The proportion of stress-induced martensite in NiTi wires increases with deflection and is lower in the compression zone than in the tension zone. The research confirmed that the crystal structure alternates between austenite and martensite under variations in stress and temperature, explaining the superelastic and thermoactivated behavior.	Dent. Mater.
Johnson (2003)	Titanium-molybdenum	Three-point bending tests (ADA)	There was significant variation between suppliers, with the range varying from small to large, depending on the nominal wire size in beta-titanium wires(TMA).	Angle Orthod
Taneja et al. (2003)	Co-axial wires (3, 5 and 6 cables)	Three-point bending tests	The stiffness of co-axial cables with multiple strands is governed by friction and internal slip.	Am J Orthod Dentofacial Orthop

Ivasishin et al. (2003)	Beta-titanium	Heat treatment, drawing, hardness, resistivity, XRD, TEM (Transmission electron microscopy), optical microscopy,	Phase precipitation and recrystallization occur simultaneously during heat treatment. Higher levels of deformation (drawing/cold work) increase the recrystallization rate and result in a smaller and more uniform grain size. Effect of Heating Rate: The heating rate to the aging temperature strongly affects the microstructure.	Metal Mater Trans
Huang et al. (2003)	NiTi	DSC, EDS, XRD, three-point tests, bending tests, traction tests, EPMA, SEM,	The presence of austenitic phases with the induction of martensitic phases, after deflection.	Nature Mater
Brantley et al. (2003)	NiTi	DSC	The study indicated that the mechanical properties vary between the wires due to differences in composition and manufacturing heat treatments.	Am J Orthod DentoFacial Orthop
Parvizi and Rock (2003)	NiTi	Three-point tests	Heat-activated NiTi produces lower forces with significant variation between commercial brands. The research highlighted the dependence temperature performance during three-point tests.	Eur J Orthod
Fischer-Brandies et al. (2003)	NiTi	DSC, SEM, bending tests	NiTi wires exhibit a biphasic structure with precipitates. Analysis revealed superelasticity, an intermediate R phase, and a significant dependence of mechanical properties on temperature.	J Orofac Orthop
Krishnan and Kumar (2004)	Stainless Steel(SS), Cobalt-Chromium, Ti-Molybdenum and Ti-Molium	Three-point bending tests, scanning electronic microscopy (SEM)	Stainless steel exhibited the highest stiffness and strength, while TMA displayed the best load-deflection characteristics (lower stiffness). TiMolium demonstrated intermediate behavior between SS and TMA, being a viable option for alignment and leveling phases that require lighter and more constant forces. Surface SEM revealed significant differences in surface roughness and integrity between the wires. TMA frequently showed a more irregular surface compared to SS.	Angle Orthod

Hayashi et al. (2004)	Stainless Steel, NiTi and Beta-titanium wires	Traction tests, bending tests	They evaluated orthodontic wires made of stainless steel (SS), NiTi, and Beta-titanium, identifying greater stiffness in SS. Superelasticity and light forces in NiTi, and an intermediate behavior with good deflection capacity in Beta-titanium. The tests indicated that Beta-titanium provides more controlled forces than SS under the same activation conditions.	Angle Orthod
Garrec and Jordan (2004)	NiTi	Bending tests	Studies have shown that the bending stiffness of superelastic NiTi orthodontic wires is not constant, varying with the martensitic phase transformation, and that increasing the cross-section there is a reduced impact on stiffness.	Angle Orthod
Garrec et al. (2005)	NiTi	Three-point bending tests at 37oC	Superelastic NiTi wires produce light, continuous forces and a high level of shape memory, with minimal plastic deformation during three-point bending tests at 37°C. The study demonstrated constant force plateaus during unloading and the phenomenon of hysteresis, with load variations depending on the archwire cross-section.	Eur J Orthod
Verstrynge et al. (2006)	Stainless Steel(SS) and Ti-Molybdenum	Scanning Electronic Microscopy (SEM), three-point bending tests; and Vickers Hardness (HV).	Beta-titanium wires offer greater flexibility and springback than SS wires, which have greater rigidity, with differences in surface topography evidenced by electron microscopy. The study concluded that, although SS is more rigid, beta-titanium wires maintain better mechanical integrity, with significant variations in physical properties depending on the manufacturing process.	Am J Orthod Dentofacial Orthop
Shaw et al. (2008)	NiTi	DSC	The analysis showed that NiTi wires exhibit temperature-dependent behavior, while TMA offered intermediate strengths and cold-worked NiTi provided greater stiffness.	Experim Tech

Kim et al. (2008)	NiTi	XRD, DSC, resistivity,SEM and Thermal Cycling Under Constant Load	Thermal cycling under constant load in NiTi stabilizes the B2→ R transformation, promoting the appearance of the R-phase during heating. The study demonstrates that the applied voltage accelerates the formation of the R-phase and improves functional stability and shape recovery.	Adv Mater Res
Iijima et al. (2008)	NiTi	XRD, TMDSC	They identified complex phase transformations in NiTi and CuNiTi wires, confirming the presence of a previously undetected low-temperature martensitic phase. Analyses demonstrated that the superelastic behavior of commercial wires is influenced by temperature-dependent structural transformations, with TMDSC revealing specific exothermic peaks within the martensite.	Dent Mater
Bolender et al. (2010)	NiTi and stainless steel and co-axial wires	Torsion tests at different temperatures	Torsional superelasticity is limited and varies according to temperature and product, being a concept applicable mainly to copper-nickel-titanium (Copper NiTi) wires activated by heat at 35°C, and not to all NiTi wires. Research indicated that, under torsion, many NiTi wires behave similarly to conventional wires, with wires exhibiting superelastic behavior being less rigid and more suitable for gentle torques.	Angle Orthod
Juvvadi et al. (2010)	Stainless steel, titanium-molybdenum alloy, and beta-titanium alloy	Toolmaker's microscope to measure the edge bevel, and x-ray fluorescence for composition analysis. Surface profilometry and scanning electron microscopy for surface evaluation. A universal testing machine to evaluate frictional characteristics, tensile strength, and 3-point bending tests.	Although SS exhibits the lowest friction, beta-titanium wire has the highest spring-back and, combined with high UTS and YS, The study compared physical and mechanical properties, indicating that titanium-molybdenum alloy (TMA) was the roughest among the three types analyzed.	Am J Orthod DentoFacial Orthop

Goldberg et al. (2010)	Polyphenylene polymers	Traction tests, Bending tests Tensile Stress Relaxation and Strain/Recovery Tests and Formabity	High-strength polyphenylene polymers are viable aesthetic alternatives to orthodontic wires, offering high springback, ductility, and moldability similar to stainless steel. The wires have demonstrated adequate continuous forces for alignment and leveling, comparable to beta-titanium (TMA) and nickel-titanium (NiTi) wires.	Eur J Orthod
Gill et al. (2010)	NiTi and Beta-titanium	MTDSC (miniaturized DSC, MEMS-DSC) and Pressure perturbation calorimetry (PPC)	Microstructure and phase composition are determined by stabilizing elements and the thermo-mechanical history, which directly influence superelasticity. The study integrated advanced calorimetry with mechanical tests to confirm that NiTi have superior superelasticity, while NiTi exhibits high strength and flexibility.	J Biomol Tech
Burstone et al. (2011)	Polyphenylene polymers	Traction tests, Bending tests and Formabity	Polyphenylene polymers (SRP/Primospire) are viable as aesthetic orthodontic wires, offering high flexibility, a smooth surface, and formability similar to stainless steel. Flexural tests indicated that these polymers are effective for the alignment and leveling phases, exhibiting strength comparable to smaller diameter NiTi and beta-titanium wires, although they demonstrate viscoelastic behavior with stress relaxation.	Am J Orthod DentoFacial Orthop
Lombardo et al.(2012)	NiTi	Three-point bending, tension tests and stress analysis, and spring tests.	Heat-activated wires offer lighter and more consistent forces upon deactivation, ideal for initial orthodontic alignment, with superelastic behavior influenced by temperature and manufacturing method.	Angle Orthod
Iijima et al. (2012)	Aesthetic Coated Nickel-Titanium (NiTi) Archwires: Woowa colored archwire with double-layer coating (silver/platinum and polymer) and BioForce High Aesthetic: BioForce High Esthetic archwire with rhodium coating	SEM, XRD, X-ray fluorescence (XRF)	Aesthetic coatings increase surface roughness in NiTi wires, with Woowa exhibiting higher deactivation strength and a polymer/silver coating, while BioForce High Aesthetic (rhodium) showed lower strength and a thinner coating. Although the surface layers altered the mechanical properties, the metallic core of all wires maintained similar hardness and elastic modulus.	Angle Orthod

Laino et al.(2012)	NiTi and Beta-titanium	DSC, DMA	Although coatings improve aesthetics, studies indicate durability challenges, such as delamination (peeling) under clinical friction and changes in properties.	J Biomater Appl
Vijayalakshmi et al. (2009)	SS, titanium molybdenum (TMA), timolium and titanium niobium archwires	Tensile strength, YS, E, load deflection, frictional properties and weld characteristics.	SS was superior in stiffness and low friction, while TMA was superior in flexibility. Timolium showed promising intermediate properties. Ti-Nb presents a low springback and high formability.	Indian J Dent Res
Varela et al. (2014)	Self-reinforced polyphenylene (SRP) thermoplastic, specifically PrimoSpire® PR-250	Tensile tests, three-point tests, friction tests, stress relaxation behavior, and formability characteristics	PrimoSpire® PR-250 self-reinforced polyphenylene (SRP) stands out as one of the stiffest unreinforced thermoplastics, possessing a "rigid-rod" structure. PR-250 offers high mechanical performance (tensile modulus of about 8.3 GPa).	Mater Sci Eng C
Kararia et al.(2015)	NiTi, Stainless Steel	Analytical and Scanning electron microscopy	Significant release of nickel and chromium ions, potential toxicity due to surface degradation.	Contemp Clin Dent
Maekawa et al (2015)	PEEK (poliéter-éter-cetona), PES (polietersulfona) e PVDF (fluoreto de polivinilideno)	Three-piont and Bending creep tests	PEEK was the best material: Among the three materials tested, PEEK showed the highest resistance to bending and creep. Comparable Properties: PEEK wires demonstrated bending and torsional properties, as well as load-deflection curves, similar to those of nickel-titanium (Ni-Ti) wires. Excellent Aesthetics and Low Absorption: PEEK (especially with new color treatments) and PVDF showed low water absorption.	Dental Mater J
Washington et al.(2015)	Synthetic fluoropolymers such as stetrafluoroethylene (PTFE), epoxy PTFE resins, or a combination of the two	Three-point bending	Although aesthetically advantageous, these coatings tend to suffer from delamination and loss of integrity, exhibiting limited clinical durability. Three-point bend tests demonstrated that such coatings generally do not significantly alter the load-deflection (force) relationship of NiTi wires, but adhesion failures can occur, resulting in inconsistent performance between different brands.	Angle Orthod

Philip et al.(2016)	Cobalt-Chromium (elgiloy)	Heat treatment and tensile tests	Heat treatment (500°C for 5 hours) increases the tensile strength of Elgiloy by 15-30% in a predictable and linear manner, with the strength varying according to the tempering process. However, the study revealed large, inconsistent variations in strength within the same tempering processes, recommending caution regarding batch uniformity.	Dent. Mater
Ilievska et al.(2016)	Ti Titanium-Niobium (Ti-Nb) alloys	XRD, SEM,DSC	The magnetic properties showed that the alloy is superconducting at 10K, and above the superconducting transition, the material is paramagnetic. The knowledge gained will allow for the estimation of the safe application of TiNb archwires, as well as during treatment.	Bulg Chem Commun
Alobeid et al.(2017)	Uncoated nickel titanium (NiTi) wires, NiTi wires with various surface modifications, and glass-fiber-reinforced composite wires	Three-point and four-point bending tests	Glass fiber reinforced composite have light strength, but a high risk of fracture at deflections above 3 mm.	J Orofac Orthop
Sepulveda et al.(2019)	CrNi	Heat treatment	Heat treatments in Cr3C2-25(Ni20Cr) (Chromium-Nickel) coatings, particularly between 300°C and 500°C, introduce new phases such as Cr7C3 and Cr23C6, impacting hardness and corrosion resistance. The study highlights that post-manufacturing treatments influence the microstructure and hardness behavior of the material.	Dental Press J Orthod
Jiayi et al. (2021)	NiTi	Molecular dynamics simulations	Precipitates in NiTi alloys (Ni3Ti, NiTi2, Ni4Ti3) decrease the phase transition temperature. The study identified the formation of an intermediate B19 phase in the transformation process from the cubic B2 structure to the monoclinic B19', driven by the interfacial energy of the precipitates.	Mater Res Express

Cayron et al. (2024)	NiTi	XRD, Density Function theory	The martensitic structure B19` of NiTi is energetically metastable, being stabilized by residual stresses rather than being in its ground state. Studies reveal that shape memory is stored microstructurally, with the structure B19´ relying on internal stresses for its stability.	Acta Materialia

The PICO strategy that we utilized for the current review was as follows: Population: Stainless steel, chromium-nickel, cobalt-chromium, beta-titanium, nickel-titanium and aesthetic wires; Intervention: Mechanical properties; Comparison: conventional alloys and Outcome: Tensile tests, three-point tests, resistivity, SEM, DSC, TMDSC, XRD and XRF analysis. So, the complete PICO strategy using Boolean operators was: (“Orthodontics” AND “Tension tests”; “Orthodontics AND three-point tests”; “Orthodontics AND torsion tests”; “NiTi AND phase transformation”; “Orthodontic wires AND mechanical properties”.

RESULTS

Study Selection

A total of 501 citations were identified by Medline and 478 by Scopus. A total of 68 articles were considered eligible for describing the basic mechanical properties of alloys and thermal tests, and tests to examine the strength of materials and the surface of the material or its cyistallography.

Study Characteristics

Table 2 shows the list of specific orthodontic articles and the types of tests used, findings as well as the source.

Metal alloys used in orthodontics

Stainless steel (SS) alloys feature corrosion resistance, good resilience and good formability. Cobalt-chromium and chromium-nickel alloys have similar characteristics to stainless steel. Titanium-molybdenum alloys have higher springback than SS alloys, good formability, but high coefficient of friction. Nickel-titanium alloys exhibit poor formability and high coefficient of friction, however many of them exhibit shape memory and superelasticity effects. Ti-Nb (niobium) and Timolium present intermediate properties in relation to SS and TMA wires. On the other hand, polymeric archwires present lower coefficient of friction when compared to metallic archwires and showed excellent ductility and sufficient resilience for the initial phases of treatment, although some of the limitations are the phenomenon of stress relaxation (creep) over time; also these archwiresdecrease in strength and present permanent deformation, which is a typical finding for viscoelastic materials, delamination and discoloration. Fig. 3 shows schematically the stiffness behavior of three metalic wires.

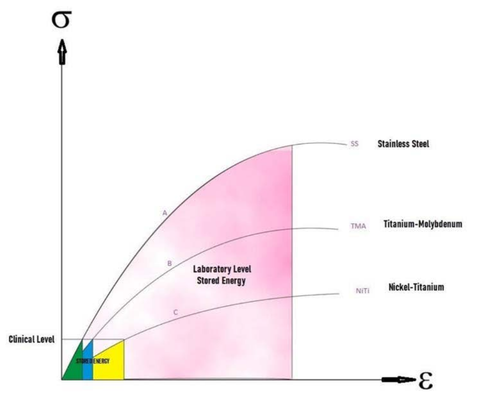

Fig. 3: Schematical mechanical behavior, under tension, of three metallic materials with different modulus of elasticity (E). A- represents the Stainless Steel (SS), B-represents the Titanium-molybdenum (Eg.TMA) and C-represents NiTi.

Stainless steel

The literature shows that the stainless steel (SS) alloys used in orthodontics are austenitic alloys (300 series, typically from group 18-8, 316-L).[1-8] In these 300´s series, the austenite alloys used in orthodontics are stabilized at room temperature. Heat treatment is indicated for these alloys for stress relief, which would lead to improved fracture resistance. Typically in iron the alpha phase (ferrite, BCC) is stable at room temperature. In special conditions and not typical in phase transformation diagrams the hexagonal compact lattice (HCP) can also produce by high pressure and temperature an orthorhombic distorted lattice and a face-centered cubic crystalline structure (FCC) structure (Fig. 4, A and C). Fig. 4(B) shows the crystalline structure for NiTi. Figure 5A-C shows cubic and tetragonal crystalline structures found in austenitic and martensitic structures in steel metallurgy. An α phase body-centered cubic (BCC) structure forms and suffer transition to a FCC (γ-austenite) structure that reverts to a BCC structure during heat treatment process.

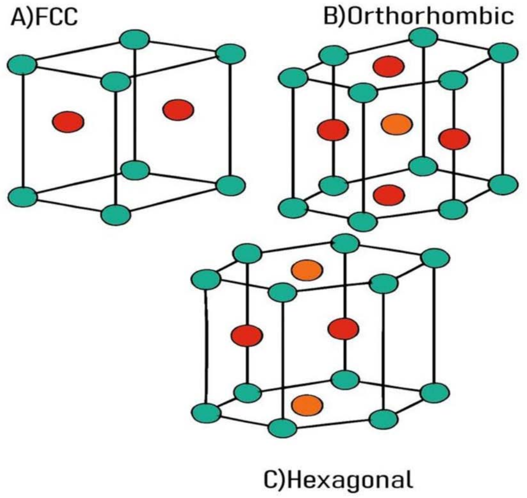

Fig. 4.A-C)Crystalline structures: A)FCC represents face-centered cubic crystalline structure (Eg: γ-austenite, primary constituent of stainless steels, 316-L); B)Orthorhombic (Eg. nickel-titanium alloys. In pure Ni and iron α-phase is formed after high pressure and temperatures, a distorted version of HCP); C) Hexagonal HCP (Eg. Pure iron under pressure; martensite in high-alloy steels; In 316-L, only in high mechanical stress conditions appears martensite structure, eg. repeated bends).

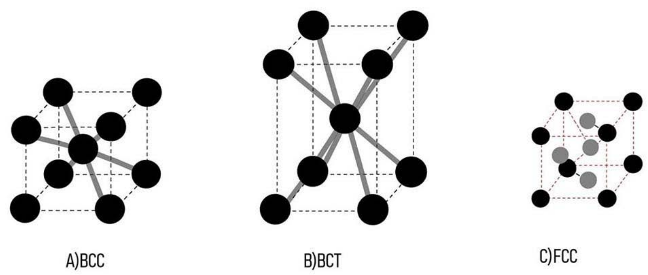

Fig. 5A-C) Crystalline structures: A)BCC represents an α phase body-centered cubic structure (Eg: iron at room temperature, ferrite; titanium-molibdenum alloys); B)BCT (Body-Centered Tetragonal) represents a body-centered tetragonal crystal (Eg: martensitic steel), Eg.Standard carbon steel; C)FCC represents a face-centered cubic crystalline structure (Eg.austenitic iron, used in orthodontics).

Chromium-nickel

Chromium-nickel (Cr-Ni) alloys[9] should not be confused with stainless steel alloys, as they do not contain the element iron in their composition, only about 80% nickel and 20% chromium. Despite having properties similar to those of SS, they are more resistant to corrosion and accept conventional welding, but they are more expensive than SS.[1-8]

Cobalt-chromium

Cobalt-chromium alloys exhibit excellent corrosion resistance, excellent ductility and fatigue resistance. They hardly fracture, even after repeated bending. After the aging heat treatment, which consists of solubilization followed by precipitation hardening for several hours, they acquire greater hardness. The increase in hardness also leads to a gain in strength and, therefore, in the yield limit (σy), thus reflecting better resistance to plastic deformation (permanent deformation) and better stored energy. There are four different degrees of resilience represented by a demarcation on the manufacturer-supplied wires, known as blue Elgiloy, yellow Elgiloy, green Elgiloy, and red Elgiloy, in order of increasing resilience. These different denominations have the same nominal composition, but different manufacturing processes, which makes them with different resilience after heat treatment. The stiffness (modulus of elasticity – E) is similar for all.[10,11]

Beta-titanium

Beta-titanium alloys (titanium-molybdenum) have superior springback and good formability, also a modulus of elasticity (E) that is twice that of conventional nickel-titanium used in orthodontics known as Nitinol, but lower than that of stainless steel. They can be welded to auxiliaries and are corrosion resistant. Crystallographic changes in the metallurgical structure, during cold working, and the drawing of alloys, during the industrial process, as well as thermal treatments performed in the office, influence their mechanical properties. They are made up of elements such as molybdenum (11.5%), zirconia (6%), tin (4.5%), incorporated in titanium (80%). Tantalum, niobium, vanadium, chromium, cobalt, nickel and iron are also present. Despite their good corrosion resistance, they are more susceptible to this process than chromium-cobalt alloys, in addition, they have a high coefficient of friction and intermediate properties between stainless steel and nickel-titanium. One of the advantages is the low potential for hypersensitivity.[12-15] Titanium-molybdenum alloys, also known as β-titanium (beta-stabilized), have a body-centered cubic (BCC) crystal structure (Fig. 5-A).

Nickel-titanium

Currently, these alloys have undergone the introduction of new elements and new heat treatments to improve their properties since the advent of Nitinol wires;[16,17] consequently austenitic-active and martensitic-active alloys are available. Austenitic-active alloys are more rigid and are not plastically deformable because they return to their original shape after unloading. Martensitic-active alloys are more ductile and plastically deformable at room temperature.[18-23] The austenitic-active alloys respond according to the applied load, which leads to a crystalline transformation called stress-induced martensite, while the martesitic-active alloys are dependent besides to an applied load, also on the temperature gradient.[12] These effects are manifested by the change in the crystalline structure of the metal (allotropic transformations), passing from one structure to another, reversibly in a dynamic equilibrium (Fig. 6). Friction due to the interatomic rearrangement between the martensite-austenite interface generates energy dissipation called hysteresis (Fig. 7). The temperature range (TTR) which is elaborated in the industry may change, depending on the type of industrial mechanical conformation (any of the spatial arrangements of a molecule) applied to the archwire.[23-29] In superelastic alloys there is an intermediate R phase (rhombohedral phase)[30-37] and an austenitic phase coexisting. NiTi exhibits a reversible R-phase transformation (B2→R→B19'). See Fig. 8. In thermoelastic alloys (martensitic-active alloys) there is a predominance of the martensitic phase.[33-38] Another titanium-based alloys as Timolium and Titanium-niobium (Ti-Nb) alloys are studied. Timolium archwire has roughly the samefrictional resistance and 50% of the rigidity of SS.[38] Niobium titanium-based alloys present high mechanical strength, excellent biocompatibility, and low modulus of elasticity. Niobium serve as a phase stabilizer of titanium.[39] They are nickel-free archwires and can be applied for the finishing and space-closure stages.[38,39]

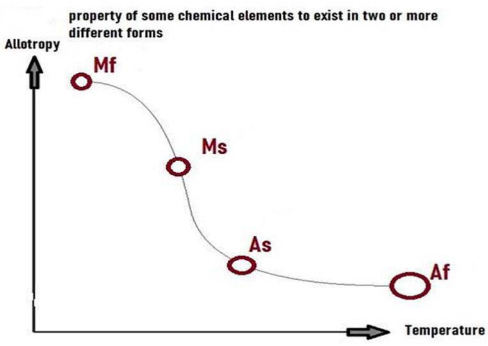

Fig. 6: Curve of the effects manifested by the change in the crystalline structure of the metal (allotropic transformations), passing from one structure to another, reversibly in a dynamic equilibrium. Temperature gradient diagram.

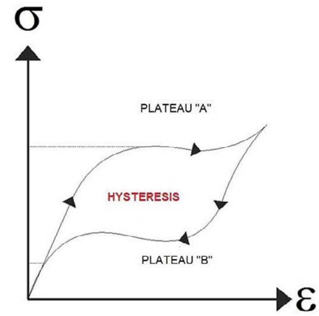

Fig. 7: Stress x strain diagram. Typical curve for a superelastic alloy, with plateaus.

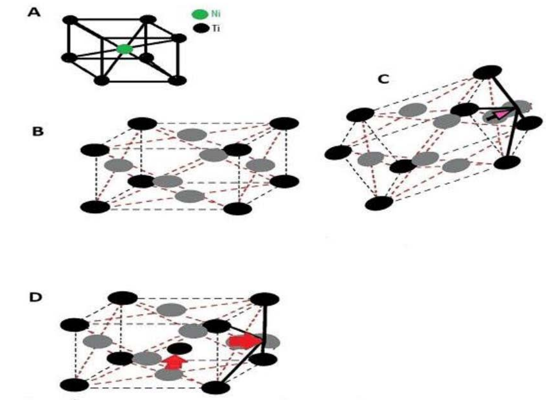

Fig. 8. A-D)Crystalline structures in shape memory crystals.A)B2(BCC-body centered cubic in austenitic phase; B) Undistorted B 19 (this is the idealized high-symmetry starting state of the parent phase before it undergoes monoclinic or orthorhombic distortion). C)B19 orthorombic (distorted and unstable); D)B 19` distorted to the stress-stabilized B 19´ structure. Arrows indicate atomic displacement. Bold lines indicate slippage of cristal orientation planes and axes.

Aesthetics wires

In general, they are made of thermoplastic polymeric materials extruded in orthodontic archwires, or even of glass fibers embedded in cured polymers. Stainless steel, titanium-molybdenum or nickel-titanium metal archwires were also developed, covered with aesthetic materials, and an undesirable effect is that their coverage may suffer wear, peeling and delamination over time.[40-44] Many of these aesthetic alloys contain silicon on the inside and a silicone coating, and eventually stain-resistant nylon, on the outside. Polymeric coatings broke easily over time.[43-47]

Translucent polymeric archwires consisting of methacrylate,butyl acrylate monomers (liquid phase), benzoyl peroxide, tricresol phosphate and silane (solid phase) have also been developed.[45] The level of viscoelastic relaxation appeared to decrease in the first 48 hours, then approached a constant value. After 80 hours there was an increase in stress due to stretching of the polymeric chains.[45,46] New alloys, metal-free based on PEEK (polyetheretherketone), PES (polyethersulfone) and PVDF (polyvinylidene fluoride) were studied and present some good properties for use as orthodontic wire.[48]

DISCUSSION

This review showed that metal alloys used in orthodontics have specific characteristics for clinical use, such as adequate rigidity, resilience, formability, low friction coefficient, low cost and biocompatibility. The crystalline arrangement (atomic scale) of the alloys used in orthodontics can be seen in Fig. 4A-C through 8A-D. The microstructure (micrometer scale) of metal alloys is determined during heat treatment and phase diagrams can show different transformation phases by which different physical properties are obtained.The microstructure refers to size and shape of the grains, their contours, and the presence of different chemical phases.These physical properties can be tested through mechanical testing as four-point bending tests, three-point bending tests, tension, and torsion tests. In metallic archwires, bending tests (eg, three-point test) allow determining the relationship between deflection and load on the wires.[49-65] Torsion tests[51,61-62] measure the degree of torsional stiffness important for evaluating the torque of the archwires on the teeth. Through tensile tests, we can obtain the elastic properties of both polymeric and metallic alloys, and thus estimate not only their degree of stiffness but also their plastic properties. These tests show that stiffness can vary considerably between manufacturers, so many nickel-titanium alloys are unable to exhibit sufficient torque to produce the desired effect. Relaxation tests[46,47](creep tests) are also commonly used to check the performance of polymeric alloys,[45] which undergo stretching at various levels and can be supported by laser strain gauges and monitored in temperature chambers. These relaxation tests can be traction or three-point deflection tests. Metallic and aesthetic alloys cannot be mechanically compared due to the fact that materials have different natures and because aesthetic alloys are viscoelastic, and thus dependent on time and strength level. The samples can be also studied using thermal analysis. An important point in studying thermal analysis used to test orthodontic wires is to know what are they for. We have the X-ray diffraction (XRD) techniques[64] that are used to know the crystal structure of metal alloys. The EDS technique that focus on quimical composition, even though both use X-ray. However, these techniques prove to be self-limiting to penetration of less than 50%. XRD has shown that in stainless steel, for example, that there are two phases, one containing an austenitic formation and the other a martensitic one. In nickel-titanium wires it also shows the phase of crystalline transformation. The X-ray fluorescence (XRF) can be found for non-destructive analysis to quantify elemental composition of a wire.[8] The differential scanning calorimetry (DSC)[65-68] technique and the more recent temperature modulate DSC (TMDSC) are effective means of accessing the thermal behavior or heat flow. The TMDSC technique[64-66] allows to obtain different signals at the same time, that is, it is capable of presenting two curves simultaneously in a separate way, for ex. the crystalline transformation stages (two-phase martensitic transformation in nickel-titanium alloys) since it makes it possible to separate the transformation stages, it is also possible to separate the martensite and R phase peaks. Laino et al67. investigated the mechanical and calorimetric properties of several orthodontic alloys by DSC and dynamic-mechanical thermal analysis (DMTA) that measures the stiffness variation while the temperature changes, also known as dynamic-mechanical spectroscopy. They concluded that the use of these two approaches together represents a complete tool for the characterization of metal alloys. In this approach, we can measure the mechanical properties of materials as a function of time, frequency and temperature, with precise control of the effort, in addition to being able to determine the modulus of elasticity of the alloys. The literature shows that there are a large number of tests which serve to measure and determine the nominal composition of orthodontic archwires. In other words, the researchercan choose the technique that best fit them according to the research objectives.

CONCLUSIONS

Metallic alloys contain specific characteristics, such as resilience, rigidity, stored energy, formability, low friction surface, low cost and biocompatibility. Stainless steel (SS) wires have the advantage of low cost and good corrosion resistance, good resilience and good formability. Cobalt-chromium and nickel-chromium have characteristics very close to SS wires but are expensive. Titanium-molybdenum alloys revealed springback superior than SS wires, good formability and high friction coefficient. Nickel-titanium based wires present poor formability, high friction coefficient, even though some of them present the shape memory effect and superelasticity. Ti-Nb and Timolium present intermediate properties in relation to SS and TMA wires. Aesthetic alloys are fragile to fracture and relaxation fatigue over time and are dependent on moisture absorption and temperature changes, and need further investigation. The properties of metallic wires are function of wire composition, variables during machining process and heat treatment.

CONFLICT OF INTEREST: None

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