A review of contemporary archwires: Their properties and characteristics

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Ideally, archwires are designed to move teeth with light, continuous forces.[1] Such forces may reduce the potential for patient discomfort, tissue hyalinization, and undermining resorption. When force is applied, the archwire should behave elastically over a period of weeks to months. To accomplish this objective, four archwire alloys are now available:[2,3] stainless steel, cobalt-chromium, nickel-titanium, and beta-titanium. Among the nickel-titanium alloys, three subdivisions exist: conventional alloy and two superelastic alloys—a pseudoelastic and a thermoelastic alloy. Each alloy system and subdivision have unique properties and characteristics. When archwires are used to treat patients, their elastic property ratios indicate that each alloy excels at a particular juncture—whether it be in the initial, intermediate, or final stages of treatment. In fact, no one wire is best for all stages, and no

archwire is ideal. Nonetheless, several properties and characteristics should be considered in the search for the ideal archwire. Among them are esthetics, biohostability, friction, formability, weldability, resilience, and springback. Unidirectional fiber-reinforced polymeric composites will provide an esthetic solution for archwires in the near future. The properties and characteristics of these different archwires are the subject of this review. Because some readers may be unfamiliar with a few of the terms used on the following pages, a glossary is provided at the end of the article. Terms included in the glossary are italicized the first time they appear in the text.

Stainless steel alloys

With the advent of stainless steels in World War I and the refinement of *drawing* processes to form wires in the late 1930s, gold archwires

Abstract

The materials used by orthodontists have changed rapidly in recent years and will continue to do so in the future. As esthetic composite archwires are introduced, metallic archwires will likely be replaced for most orthodontic applications in the same way that metals have been replaced by composites in the aerospace industry. Archwires are reviewed in the order of their development, with emphasis on specific properties and characteristics, such as strength, stiffness, range, formability, and weldability. Because an ideal material has not yet been found, archwires should be selected within the context of their intended use during treatment.

A glossary of terms is provided.

Key Words

Archwires • Esthetics • Materials • Mechanics • Properties

Figure 1
Two grains of stainless steel and the deleterious clinical consequences that occur when chromium carbides are formed nearby. When improperly cooled, the chromium diffuses toward the carbon-rich areas, which are often in the grain boundaries. If the chromium content is measured along the line, A-B-C-D, the depletion of chromium below the prerequisite amount of about 11% can be seen contiguous to the chromium-rich carbides within the grain boundaries. As a result, stainless steel corrodes in the chromium depleted areas via the process called sensitization. (Adapted, in part, from ref. 8.)
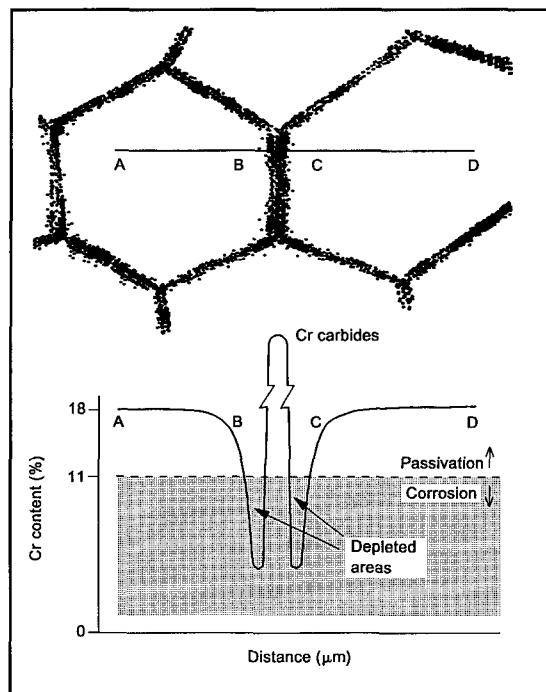
Figure 2
Influence of heat treatment on the ultimate strength (proportional to the maximum force at "X"), the resilience (proportional to the area under the initial linear portion of the force-displacement curve), and the formability (displacement in the plastic area just prior to failure at "X") of four cobalt-chromium alloys (clockwise from top left):[17] soft ("blue"), ductile ("yellow"), semi-resilient ("green"), and resilient-high spring temper ("red"). (To convert kg to N, multiply by 9.8.)
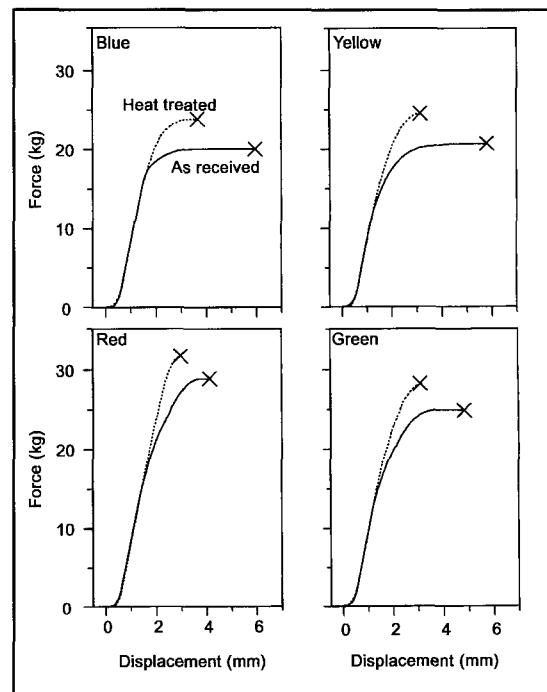

Figure 1

Figure 2

gradually lost favor to the smaller cross-sectional areas that stainless steel archwires could provide. By the 1950s the type 300 series of stainless steel alloys were used for most orthodontic materials. These typically contained 17 to 25% chromium and 8 to 25% nickel, with the balance being iron.[4] When at least 10 to 13% chromium was present in the alloy, a *coherent* oxide layer formed that *passivated* the surface, thereby rendering the alloy "stainless."[5] When at least 8% nickel was present, the single phase structure of *austenite* was stabilized, and the overall corrosion resistance was enhanced.[6] Carbon content was purposely maintained below 0.20%[7] to reduce the formation of chromium carbides (Figure 1), structures that can ultimately foster the corrosion of austenitic steels. Stainless steels were strong, typically about five times stronger than structural girders,[9] and their stiffnesses were 93 to 100% that of conventional carbon steels.[10] These stainless steels were also sensitive to the products of incomplete combustion, such as those found in a sooty flame, and could not be cooled slowly through the temperature regime of 425 to 815°C or else *sensitization* to corrosion could occur.[11] (To convert °C to °F, multiply by 1.8 and add 32.) As the '50s came to a close, Rocky Mountain Orthodontics was offering two *tempers* of *cold-worked* stainless steels: a standard and an extra hard grade. Today, American Orthodontics advertises three grades of stainless steel wire: a Standard™, a Gold Tone™, and a Su-

per Gold Tone™.[12] Stainless steel, however, was not destined to enjoy the predominance in the marketplace that gold had enjoyed for so many years before.

Cobalt-chromium alloys

Also in the 1950s, the Elgin Watch Company was developing a complex alloy whose primary ingredients were cobalt (40%), chromium (20%), iron (16%), and nickel (15%).[13] This cobalt-chromium alloy was marketed as Elgiloy™ by Rocky Mountain Orthodontics. In addition to having similar *stiffness* characteristics as stainless steel, the alloy was capable of having its *strength*, and more importantly its *formability*, modified by *heat treatment*.[14] At that time practitioners particularly welcomed the formability before heat treatment in order to bend loops into wires and to enhance the working *ranges* of their otherwise somewhat rigid appliances. Once the appliance was fabricated, however, the practitioner no longer required the formability. Instead, he or she desired resilience in order to capitalize on the inherent elasticity of the material, which could be achieved by heat-treating the alloy at 482°C for 7 to 12 minutes.[15] This so-called *precipitation hardening* heat treatment[16] increased the *ultimate strength* and *resilience* of these archwires without changing the stiffness (Figure 2). Indeed, four such products were eventually marketed that varied in initial formability from a hard and resilient-high spring temper alloy, designated "red," to

a soft and formable alloy, designated "blue." Two of these, the blue alloy and a slightly less formable but nonetheless ductile "yellow" alloy, were developed between 1958 and 1961 in order to match, in their heat-treated states, the temper of the standard and extra-hard stainless steels of the day.[18] At that time in the evolution of materials, wire size and shape generally dominated over structural properties, owing largely to the fact that the stiffnesses of all materials were virtually identical.

Nickel-titanium alloys
Conventional nitinol

In the late '60s, the Office of the Navy was actively studying new types of alloys that exhibited a *shape memory effect* (SME).[19] One of these, a nickel-titanium alloy, showed great promise and was dubbed nitinol, an acronym for nickel-titanium Naval Ordnance Laboratory. This alloy was capable of being deformed, clamped, heated, and cooled into a specified shape, so that when it was later deformed into a new shape and subsequently heated, the material would remember its previous post-heat treatment shape.[20,21] Around 1970, Dr. George Andreasen recognized the potential of this alloy.[22] Largely through his efforts and those of the Unitek Company, the first nitinol alloy was marketed to orthodontists as Nitinol™. Ironically, this first 50:50 composition of nickel and titanium was a shape memory alloy in composition only (Figure 3). Indeed, this alloy was *passive*, as the SME had been suppressed by cold working the wire during drawing to more than 8 to 10%.[24] What was so attractive about this martensitic stabilized alloy was its low force per unit of deactivation—that is, its low stiffness. Compared with the competition of the day, this wire was quite springy—delivering only one-fifth to one-sixth the force per unit of deactivation[25] and thereby better meeting the criterion of light, continuous force. And, like all of its wire predecessors, its stiffness was linear like a spring, resulting in an equal loss of force for a fixed increment of deactivation.[26] When this stiffness was combined with its outstanding range and high *springback*, one might presume that this wire was the ideal. It didn't take long, however, before its lack of formability was recognized as a limitation, especially when wires broke. The lack of formability largely remains today, but the initial brittleness that plagued the early nitinol product has long since been rectified.
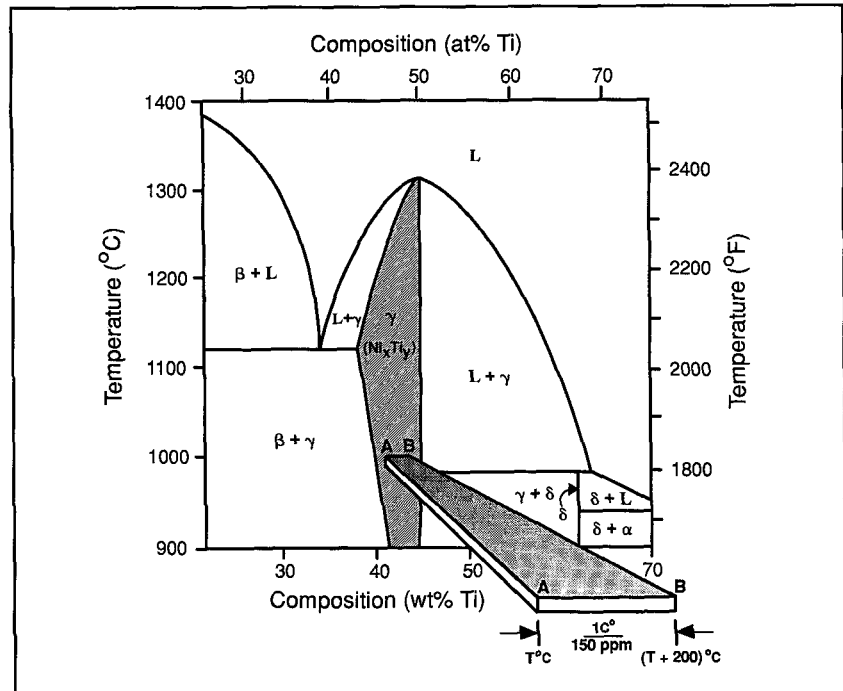

Figure 3

Pseudoelastic nitinol

In addition to this martensitic stabilized alloy, two other generic nitinol-type alloys are available today that are *active*, that is, they undergo some form of SME[27] and are superelastic: an austenitic active alloy and a martensitic active alloy. In the austenitic active alloy, both the martensitic and austenitic *phases* play an important role during its mechanical deformation. *Martensite* represents the low stiffness phase having an *elastic modulus* of 31 to 35 GPa[26] (to convert GPa to Pa, multiply by 10^9; to convert Pa to psi, divide by 6.9×10^3) and an ultimate strength of about 1.4 to 1.7 GPa;[28,29] austenite represents the high stiffness phase having an elastic modulus of 84 to 98 GPa[28] and an ultimate strength of about 0.84 GPa.[30] (To place these values in perspective, the elastic modulus [200 GPa] and ultimate strength [2.1 GPa] of stainless steel archwires should be compared.[29]) Thus on loading, the austenitic active alloy starts with a slope (stiffness) that produces some three times the force per activation of the conventional martensitic stabilized nitinol alloy[24] (Figure 4). Fortunately this effect is short-lived and gives way to a long plateau-like area. At first glance one would suspect that the mechanical properties are dismal; but perseverance prevails, as eventually a positive slope reoccurs wherein the stiffness is comparable to that of martensitic nitinol. In fact, a stress-induced *phase transformation*[31] has occurred in which the austenitic phase of this

Figure 3
Simplified phase diagram of nickel-titanium alloys highlighting the *nonstoichiometric compound*, γ or Ni_xTi_y (shaded area), wherein the shape memory alloys may be found. The figure also illustrates the sensitivity of the phase transformation with composition; namely, that a 3% change in composition from A to B can change the transformation temperature of this intermetallic phase by 200 Celsius degrees. (Adapted, in part, from ref. 23.)
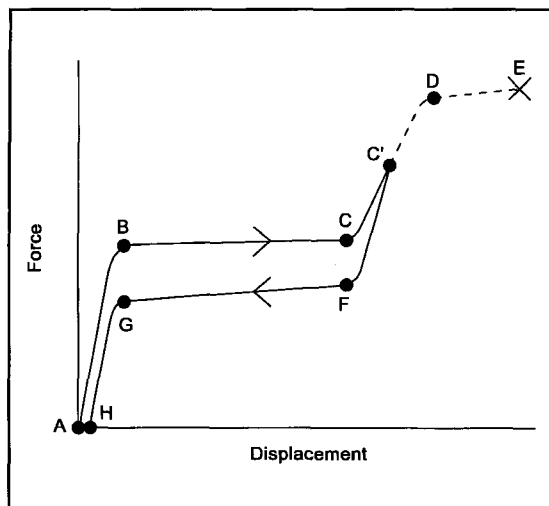
Figure 4

Figure 5

Figure 4
Illustration of pseudo-elasticity showing high modulus austenitic regions (A-B and G-H), phase transition regions from austenite to martensite (B-C) and from martensite to austenite (F-G), and the martensitic regions (C-E) and (C'-F). Note that the slopes of the austenitic moduli on loading (A-B) and unloading (G-H) should be about three times greater than the slopes of the martensitic moduli on loading (C-C') or unloading (C'-F). These latter two lines have been slightly offset from one another for clarity. (Adapted from ref. 31.)

Figure 5
Illustration of the thermally induced shape memory effect (SME) that is created via a combination of the pseudo-elastic effect (A-B at the temperature, T_1) and the thermoelastic effect (C-A at the temperature, T_2). (Adapted, in part, from ref. 32).
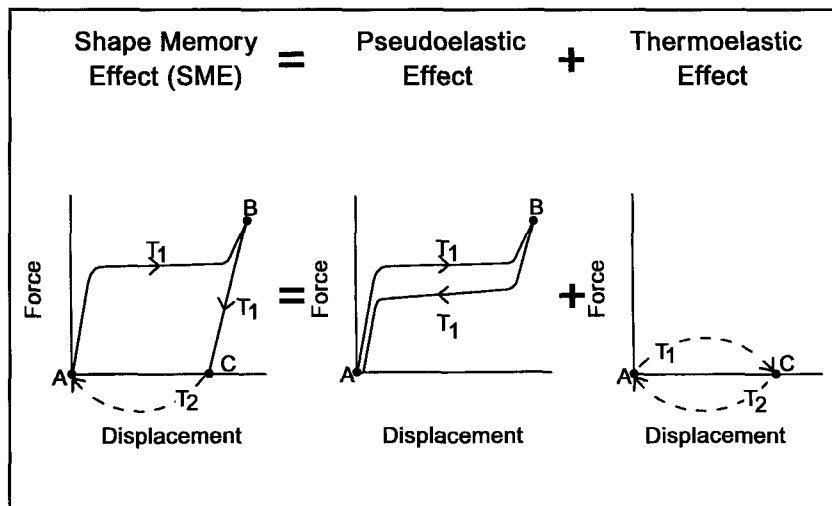
nitinol wire has transformed to the martensitic phase. Upon deactivation the reverse occurs, as the linear region that is associated with the martensitic phase of a conventional alloy gives way to a second plateau region at a lower force. Here, the martensitic phase is being gradually transformed to the austenitic phase. When this stress-induced transformation is complete, the initial high slope associated with an austenitic phase is revisited. Because the springback is nearly total, this series of clinical events is elastic despite the fact that the appearance is quite nonlinear. The second plateau region, in which martensite reversibly transforms to austenite and thereby changes shape to maintain force, represents the key attribute of this nonlinear but nonetheless elastic alloy and is called *pseudoelasticity*.[32] In clinical terms, a practitioner can now align teeth or close space with a constant force, providing that he or she has activated the archwire within the plateau region. This feature of stress-induced, active austenitic archwires makes them unique within the orthodontist's armamentarium.

Today several alloys are being marketed that utilize pseudoelasticity. The latest of these, 27°C Superelastic Copper Ni-Ti™, contains alloy additions of nominally 5 to 6% copper and 0.2 to 0.5% chromium. According to its manufacturer,[33] this product is an austenitic active wire whose copper additions increase its strength and reduce the energy lost as measured by the area within its first and second plateau regions (cf Figure 4; A-C' and C'-H). Unfortunately, these benefits occur at the expense of increasing its phase transformation temperature above that of the ambient oral cavity. To compensate for this unwanted effect, 0.5% chromium is added to return the trans-

formation temperature to 27°C. Two other alloys are also available from this family of nickel-titanium-copper-chromium alloys—one that has a transformation temperature of 35°C and another that contains 0.2% chromium and transforms at 40°C. Because the transformation temperatures of these latter two wires are higher than the aforementioned first wire, they will increasingly be influenced by temperature as they represent the third type of nitinol alloys described below.

Thermoelastic nitinol

The third nitinol-type alloy on the market today is a martensitic active alloy that ultimately exhibits a thermally induced SME (Figure 5). This is the long-awaited nitinol alloy that Dr. Andreasen hoped to someday employ in orthodontics.[34,35] For many years the alloy composition simply could not be controlled precisely enough to make a uniform wire product. Transition temperatures from martensite to austenite had to occur in the region of ambient oral temperature, and yet it was known that for every 150 parts per million (ppm) variation in composition, a 1C° change in the transition temperature occurred[28] (Figure 3). After a 20-year hiatus, Miura[36] showed that surgical cases could be treated by preparing a series of arches in which the desired shape was set by heat. Upon distortion and insertion into the patient's mouth, the appliance would be activated by the warmth of the oral cavity and return to its predetermined shape. By capitalizing on *thermoelasticity*,[32] a series of final arch forms could be generated, and thereby the practitioner could maintain control. Using these alloys, major medical advances have been made in the People's Republic of China for the treatment of scoliosis.[37] In this procedure a patient has pre-
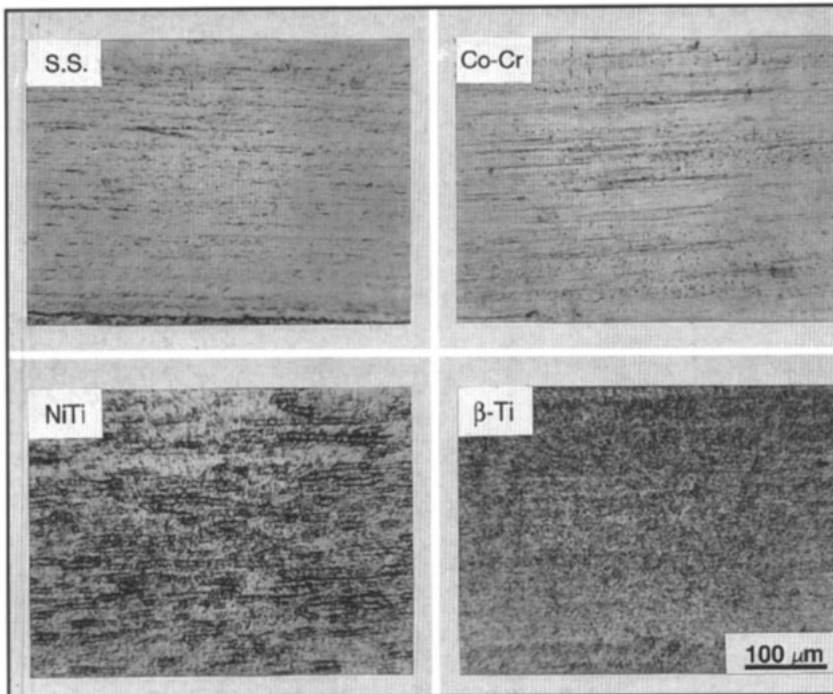
Figure 6

Figure 7

cooled shape memory rods implanted in his or her back, following which the body heat warms the rods over a period of a few hours, and the spine is gradually straightened. In the next few years orthodontists will hopefully achieve similar dramatic results by reducing undesirable effects (such as round-tripping) and consequently adapt and control shape memory alloys for the routine treatment of malposed teeth. Today, the thermoelastic effect is demonstrated in GAC International's alloy, Sentalloy™ Light.

Beta-titanium alloys

The last major alloy system to have an impact on current clinical orthodontics was introduced around 1980. Stabilized beta-phase titanium alloys contain about 80% titanium. In addition, they include 11.5% molybdenum, 6% zirconium, and 4.5% tin.[38] Historically, pure titanium has a stiffness (102 GPa) that is about one-half that of stainless steel;[39] the stiffness subsequently varies from 99 to 127 GPa upon alloying to form the conventional type of alpha-phase titanium alloys.[40] For orthodontic use, one of Dr. Burstone's primary objectives was to produce an alloy whose deactivation characteristics were about one-third that of stainless steel or twice that of a conventional martensitic stabilized nitinol.[2] This led to Ormco Corporation's introduction of the low-stiffness beta-phase titanium-molybdenum alloy known as TMA™. Advantages of this alloy

were several. When compared with nitinol, TMA was inherently smoother[41] (Figure 6), could be welded, and had good formability. Moreover, when compared with stainless steels, TMA produced gentler linear forces per unit of deactivation and had substantially more range and higher springback. Indeed, TMA was almost the perfect wire, since its characteristics were so balanced. Yet TMA, too, had a latent flaw—the *coefficients of friction* were the worst of any of the orthodontic alloys,[42] and consequently its ability to accommodate the sliding of teeth was limited (Figure 7).[43-45] Ironically, the first alloy to be used during this modern era of orthodontics, stainless steel, remains the best in this regard.[42]

Applying archwires

Having summarized the state of the art of archwires over the last 50 years, let's explore how they complement and supplement one another in everyday practice by applying the concepts of *elastic property ratios*.[29] In this regard, some reference to the strength, stiffness, and range would be appropriate as a function of the different stages of treatment (Figure 8). During the initial stage of treatment, where initial leveling and alignment are desired, great range and light forces are sought. By referencing elastic property ratios of strength, stiffness, and range, two principal types of wires are suggested: either a multistranded stainless steel wire or a nitinol-type wire. The former capital-
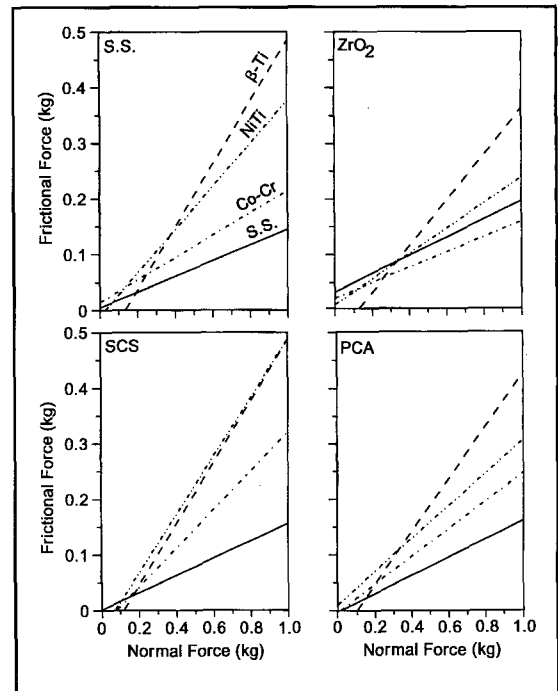
Figure 6
Optical photomicrographs show the relative smoothness of the typical archwires made from stainless steel (S.S.), cobalt-chromium (Co-Cr), beta-titanium (β-Ti), and nickel-titanium (NiTi). Beta-titanium is inherently smoother than nickel-titanium. Unfortunately, smoothness is not a sufficient condition for low friction (cf Figure 7).

Figure 7
Coefficients of kinetic friction of the typical as-received archwires (as determined from the slopes of half the drawing force against the normal force) coupled with typical as-received brackets (clockwise from top left): stainless steel (S.S.),[43] zirconia (ZrO$_2$),[44] polycrystalline alumina (PCA),[43] and single crystal sapphire (SCS).[45] Note that these β-Ti archwires (– – –) always displayed the greatest slopes and hence the highest coefficients of friction, while S.S. archwires (—) had the lowest slopes.

Figure 8
Requirements of elastic properties (i.e., strength, stiffness, and range) as the stages of treatment progress. From the interrelationship between these three elastic properties (i.e., strength = stiffness x range)[29] and the requirements of the practice, the corresponding nominal values are adduced at different stages of treatment.

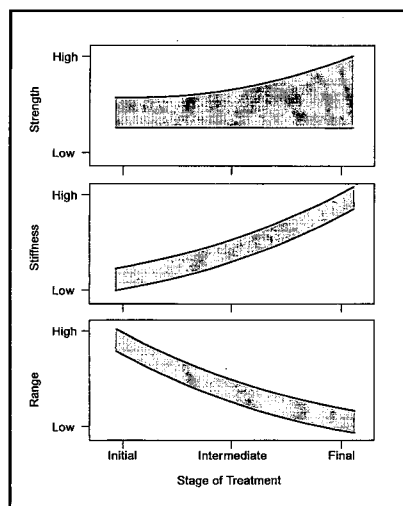**Figure 9**
Criteria of an ideal archwire. Note that, although esthetics is important, good performance characteristics viz a viz mechanical properties are among the necessary conditions for clinical acceptability. Being a poor biohost, having weldability, and possessing good biocompatibility are the other necessary conditions.

Figure 8

Figure 9

izes on conventional variable cross-section orthodontics, which was tabulated many years ago in an orthodontic textbook by Dr. Raymond Thurow.[46] The latter makes use of variable modulus orthodontics[47] in which three of the four principal alloys in use today have different stiffnesses for the same shape and size of archwire. As treatment progresses into the intermediate stage, beta-titanium alloys become advantageous as their formability, springback, range, and modest forces per unit deactivation become favorable. Larger sizes of nitinol can still be useful here, however, if an 0.022 inch slot is employed. If sliding mechanics are required, undersized stainless steel wires may be used. As the orthodontic patient progresses to the final stage of treatment wherein more arch stability and small tooth movements are required, wires having substantial stiffnesses but limited ranges are acceptable. Consequently, large gauges of beta-titanium or stainless steel wires may be used to maintain arch form while making small rotational, translational, or tipping motions. Exactly which alloy is used here depends on the details of the case—that is, whether it is more important to have more range, as afforded by a beta-titanium wire, or more stiffness, as afforded by a stainless steel wire.

In search of the ideal archwire

From this brief description of contemporary archwire alloys we see that no ideal archwire exists. This conclusion is not surprising because the demands of the tre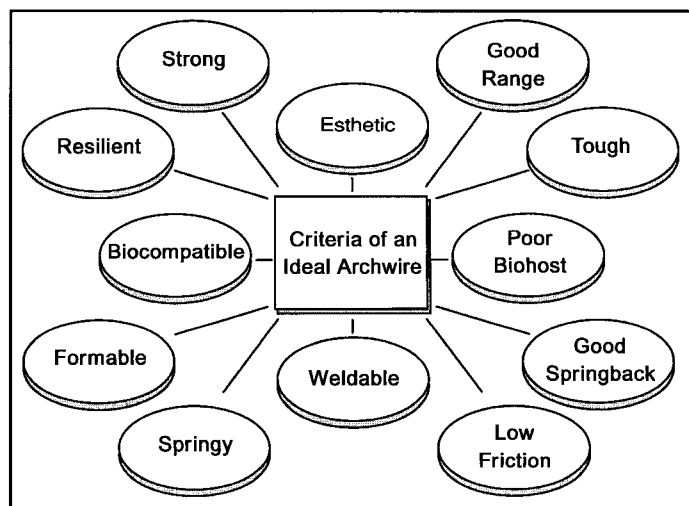atment plan require different characteristic stiffnesses and ranges. Nonetheless, several desirable characteristics would be appropriate to list (Figure 9), a few of which will be highlighted. Here, the outcome will vary. That is, specific wires will do some things well and others poorly; but no wire will do it all.

Wires should be esthetic. No wire today meets this criterion, although manufacturers have tried. When coated,[48] white-colored wires have routinely succumbed to the forces of mastication and/or the enzyme activity of the oral cavity. When uncoated,[49] transparent wires have had such poor mechanical properties that they function merely as a placebo. Although esthetics are important to the orthodontist, function is paramount. Anything less is unacceptable.

Wires should have poor *biohostability*. This characteristic goes beyond biocompatibility—that is, the achievement of compatibility of non-living implant materials with the body—in that good biocompatibility is a prerequisite. As a poor biohost, however, the ideal archwire should neither actively nurture nor passively act as a substrate for micro-organisms that will smell foul, cause color changes that detract from esthetics, or remove and/or build up material that compromise mechanical properties. These restrictions apply to spores and viruses as well.

Wires should possess low coefficients of friction, independent of whether they are bathed in saliva[50] or whether the hydrodynamic boundary layer between archwire and bracket has been breached by the dry state.[43,50] In this
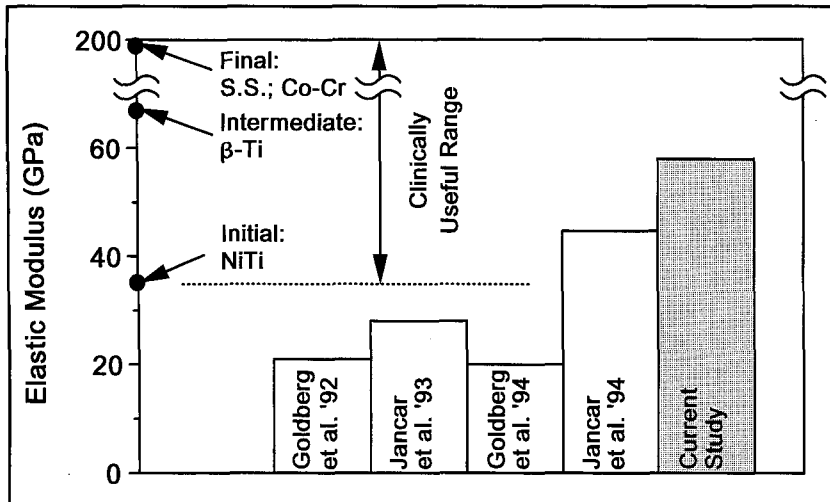
Figure 10

Figure 11

regard, titanium wires are inferior to stainless steel,[51] although some progress has been made to improve the coefficients of friction of beta-titanium via ion implantation technology.[52]

Finally, wires should have formability, *weldability*, resilience, and springback so that they may be deformed into loops or bends, fused onto a clasp, employed to maximize their stored elastic energy, and ultimately return to their initial shape.

The future: Esthetic archwires

One promising approach toward achieving an esthetic archwire with excellent overall properties involves the use of *composites*,[53] which can be composed of ceramic fibers that are embedded in a linear or crosslinked polymeric matrix. Existing experimental prototypes are tooth colored, can be as strong as the strongest piano wire, and can vary in stiffness from that of the most flaccid multi-stranded archwire, to nearly that of a beta-titanium archwire[54-59] (Figure 10). These characteristics can be varied during manufacture without any change in wire-slot engagement by *pultrusion*,[60] in which the relative proportions of the fiber and matrix materials are adjusted appropriately and cured by electromagnetic radiation.[61] Mechanical tests show that such archwires are elastic until failure occurs. When compared with NiTi, resilience and springback are comparable (Figure 11). Moreover, when failure finally does occur, the wire loses its stiffness, but it remains intact. Although the specifics of other characteristics, such as formability, weldability,

and frictional coefficients, are unknown at this time, preliminary experiments suggest that preformed archwires and rectangular cross-sections should be possible by a process known as *beta-staging*[59] and that low coefficients of friction and enhanced biocompatibility should be possible by modifying the surface chemistry of the polymer.[63] Indeed, as composites are displacing metallic alloys as structural components in the aerospace industry, the expectation is that the attractive properties and characteristics of these esthetic composites will capture a significant share of the marketplace within the next decade.

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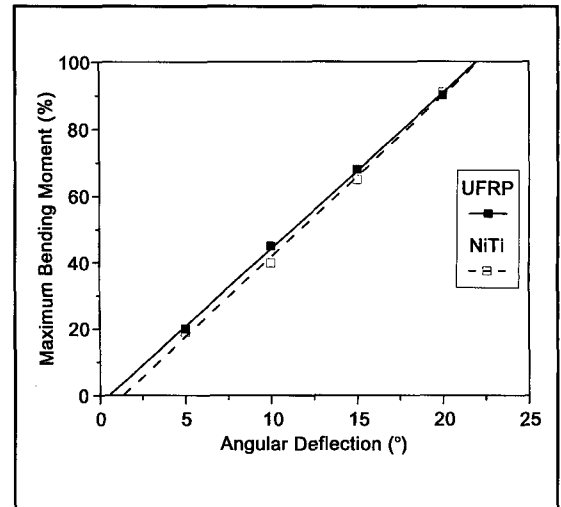University of North Carolina
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Figure 10
Present status of pultruded composite technology (shaded bar)[58,59] compared with other plastic composites (open bars)[54-57] and conventional archwire products (black bullets).[25,29] All other things being equal (i.e., archwire size, shape, engagement, etc.) and independent of whether the archwire is made of metal, ceramic, or composite, the elastic modulus should be comparable to NiTi in order to level and align the teeth during the initial stage of treatment but need not exceed S.S. or Co-Cr in order to stabilize the arch in the final stage of treatment. In this regard contemporary plastics, with elastic moduli that vary from 3 to 7 GPa, are unsuitable for orthodontic archwires.

Figure 11
Comparison of a prototype composite archwire (unidirectional fiber-reinforced polymeric composites or UFRP) to a conventional nickel-titanium archwire (NiTi) in bending. Note that, when perfected, composite archwires will possess the stiffness and esthetic characteristics desired by practitioners and patients.[62]

Glossary

active - A term that is used to describe an alloy that is capable of undergoing its anticipated *phase transformation*.

austenite - Historically, austenite refers to a specific *phase* of iron and steel alloys that has a face-centered cubic structure. Today, the high-temperature *phase* of nickel-titanium alloys is sometimes called austenite because, like many ferrous alloys, this austenite can transform to *martensite*, too.

beta-staging - During *pultrusion*, an intervening process in which the partially-cured resin and its bundles of continuous fibers are deformed into another form (e.g., a preformed archwire), after which curing is completed.

biohostability - The ease with which a material will culture bacteria, spores, or viruses.

composite - A multiphase material composed of metals, ceramics, and/or polymers that is artificially made. The resulting *phases* are chemically dissimilar and separated by distinct interfaces.

coefficients of friction - In archwire-bracket couples, the ratio of half the drawing force that pulls the archwire through the bracket slot to the normal force that presses the archwire into the bracket slot. When motion is impending, the coefficient of friction is termed "static"; when motion is occurring, it is termed "kinetic." The coefficient of friction is a constant, independent of apparent area of contact but not usually independent of sliding velocity.

coherent - Refers to an oxide layer, which has the same crystalline structure as the substrate that it *passivates* from corrosion. This coherency makes the oxide layer particularly tenacious. Aluminum oxide on aluminum is an example of a coherent oxide; rust on iron is one example of an incoherent layer.

cold-worked - The process of plastically deforming a metal at a temperature below that at which it recrystallizes new grains, which is usually one-third to one-half times its absolute melting point temperature. Consequently, cold-

working can proceed below room temperature as well as above room temperature, depending on the alloy. In contrast "hot-working" (the process of plastically deforming a metal at a temperature above that at which it recrystallizes new grains) can proceed below or above room temperature, too, depending on the alloy.

drawing - A forming process that is used to fabricate metal wire and tubing. Deformation is accomplished by pulling the material through a die by means of a tensile force applied to the exit side of the die.

elastic modulus - An engineering property of a material that equals the ratio of stress to strain, when deformation is totally elastic. In tension or bending the elastic modulus is often called "Young's modulus."

elastic property ratios - Ratios of *strength, stiffness,* or *range* between two archwires within the elastic region of their mechanical behavior that are used to compare archwires composed of different materials or having different geometries.

formability - The ease with which a material may be permanently deformed as measured, for example, by the magnitude of the difference between the elastic *range* (which occurs at the proportional limit) and the *range* at failure.

heat treatment - General process of using thermal energy to change the characteristics of metallic alloys as in *tempering, precipitation hardening,* or annealing (a high-temperature, softening process).

martensite - Historically a metastable iron *phase*, which is supersaturated with carbon, that results from the diffusionless transformation of *austenite* following rapid cooling. This formation of martensite requires the cooperative movement of atoms, which result in a continuous *phase transformation* from one crystalline structure to another. Today, the product of such a transformation (e.g., in a nickel-titanium alloy) will be called martensite whether it is thermally activated (termed "iso-

thermal") or not thermally activated (termed "athermal").

nonstoichiometric compound - An ionic compound in which the number of positively-charged atoms and/or negatively-charged atoms is not an integral number as it is in common salt (NaCl), wherein the formula number of Na and Cl atoms both equal 1.

passivate - Process of protecting a material from corrosion by specific alloying, surface coating, or *heat treatment*, for example.

passive - A term that is used to describe an alloy that is incapable of undergoing its anticipated *phase transformation* because extensive plastic deformation has suppressed the transformation.

phase - A homogeneous portion of a material system that has uniform physical and chemical characteristics.

phase transformation - A change in the number and/or character of the *phases* that constitute the microstructure of an alloy by a change in crystalline structure.

precipitation hardening - The process by which a metal alloy is hardened and strengthened by extremely small and uniformly dispersed particles that precipitate from a supersaturated solid solution. (Iced tea with lots of sugar is an example of a supersaturated liquid solution.) Precipitation hardening is also called "age hardening" because it requires time to harden an alloy.

pseudoelasticity - The mechanical analog of *thermoelasticity* in which, at constant temperature, the austenitic-to-martensitic *phase transformation* occurs with increasing applied force. As the force is subsequently removed, the reverse *phase transformation* occurs.

pultrusion - The process of manufacturing components having continuous lengths and a constant cross-sectional shape, such as in archwires. During production, bundles of continuous fibers are impregnated with a polymeric resin, pulled through a sizing die that preforms the composite as it establishes the resin/fiber ratio, and passed through a curing die that imparts the precise shape as it cures the resin.

range - The distance that an archwire can be activated by a specific force. This distance is termed the "working" range, when an orthodontist defines the limit of activation. With regard to *elastic property ratios*, one measure of the range is the distance that an archwire can be activated elastically (i.e., its elastic range), which terminates at its proportional limit.

resilience - The capacity of a material to absorb energy, when the material is elastically deformed. Resilience is measured by the area under the elastic portion of the engineering stress-strain curve.

sensitization - In austenitic stainless steels such as those used in archwires, the formation of chromium carbides by locally depleting chromium from adjacent regions, thereby compromising the corrosion resistance. Although sensitization occurs upon prolonged heating or slow cooling in the critical temperature regime of over 425 to 815°C, sensitization can occur in as little as a few seconds at 650°C.

shape memory effect - The combination of *thermoelasticity* and *pseudoelasticity* in which, following a force-induced *phase transformation*, the reverse transformation occurs, when the archwire temperature is increased to oral temperature, for example.

springback - The extent to which the *range* recovers upon deactivation of an activated archwire.

stiffness - In archwires, the ratio of the force required to exceed the elastic region to the distance that an archwire can be activated elastically. With regard to *elastic property ratios*, the stiffness equals the quotient of the *strength* to the *range* within the elastic region.

strength - The force required to activate an archwire a specific distance. With regard to *elastic property ratios*, one measure of the strength is the force that an archwire can withstand elastically (i.e., its elastic limit), which is similar in magnitude to its proportional limit.

temper - A *heat treatment* that occurs at low temperatures (typically 200 to 650°C) that enhances toughness and ductility. In ferrous alloys, tempering is particularly important to transform brittle *martensite* into tempered *martensite*.

thermoelasticity - The thermal analog of *pseudoelasticity* in which the martensitic *phase transformation* occurs from *austenite* as the temperature is decreased. This *phase transformation* can be reversed by increasing the temperature to its original value.

ultimate strength - Maximum engineering strength experienced by a material in tension. Hence the term, "ultimate tensile strength," is often used.

weldability - The ease by which metals may be joined by actually melting the work pieces in the vicinity of the bond. A filler metal may or may not be used to join the work pieces.

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