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A Comparative Study of Tensile Properties in Five Orthodontic Wires

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ABSTRACT

A COMPARATIVE STUDY OF TENSILE PROPERTIES IN FIVE ORTHODONTIC WIRES

by Charles B. McDermott

The tensile properties of .017 x .025" stainless steel, Multiphase, Blue Elgiloy, beta titanium, and Nitinol were tested and compared. All wires were tested in the "as received"condition. Fifteen samples of each type of wire were tested in order to determine the (1) modulus of elasticity, (2) .2% yield strength, (3) ultimate tensile strength, (4) percentage elongation and (5) maximum elastic deflection.

The modulus of elasticity and .2% yield strength are the most important properties to orthodontists because of their influence on the wire's stiffness, strength and range. The ratio of yield strength/modulus of elasticity, termed maximum elastic deflection, gives a measure as to the range of a wire, which is how far a wire can be deformed without exceeding its working limits. The ultimate tensile strength is the maximum load that the wire can withstand before fracture, while the percent elongation is an indication of the ductility of a wire.

Stainless steel, Multiphase, and Blue Elgiloy showed very similar properties while beta titanium and Nitinol exhibited a modulus of elasticity that was one-half to one-fourth (respectively) that of the stainless steel and chromiumcobalt alloys in the untreated conditions. For stainless steel, Multiphase and Elgiloy the percentage elongation was

between 1.5 - 2.0% while that of beta titanium and Nitinol was 3.0 and 8.6% respectively. Both beta titanium and Nitinol had more favorable maximum elastic deflection ratios than the other three wires, indicating that they would have a larger range in their activations. Stainless steel had the largest .2% yield strength and tensile strength, while Nitinol exhibited the smallest .2% yield strength; beta titanium had the smallest tensile strength value.

The similar properties of stainless steel, Multiphase and Elgiloy produce forces that are more dependent upon the dimensional size of the wire rather than the wire type. Both beta titanium and Nitinol had properties that differed a great deal from the other three wires and would require larger sizes to produce forces of equal magnitude to that of steel or chromium-cobalt wire.

LOMA LINDA UNIVERSITY
GRADUATE SCHOOL

A COMPARATIVE STUDY OF TENSILE PROPERTIES IN FIVE ORTHODONTIC WIRES

by

Charles B. McDermott

A Thesis in Partial Fulfillment of the Requirements
for the Degree Master of Science in Orthodontics

June 1981

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INTRODUCTION AND REVIEW OF THE LITERATURE

The literature provides results from reseachers who have reported experimental test values for various wires. Goldberg and Burstone explored modulus of elasticity, .1% yield strength and maximum elastic deflection for both beta titanium and stainless steel in .03" diameter.[5] Andreasen and Morrow determined ultimate tensile strength and modulus of elasticity on Nitinol and stainless steel of various sizes.[1] Blue Elgiloy, Yellow Elgiloy, and Multiphase of .016 x .022" dimension were tested by Harrison for tensile properties of percentage elongation, yield and tensile strengths, and modulus of elasticity.[6] Jackson measured these same tensile properties on various brands of stainless steel in .02" diameter.[7] Twelftree's research involved Yellow Elgiloy and six other stainless steels of .016" diameter. He measured proportional limit, ultimate tensile strength, modulus of elasticity, and three different percent yield strengths.[13] Due to differences in wire size, which can influence tensile strengths, and variations in methodology between researchers, it is difficult to directly compare results of one wire to another. It was determined to test five types of wires of equal .017 x .025" dimensions on the same calibrated machine so valid comparisons could be made between wires. The wires tested were stainless steel, Multiphase, Blue Elgiloy, beta titanium, and Nitinol.

Advances in orthodontic metallurgy, in recent years, has improved both appliance efficiency and patient comfort. Precious metals were used until around 1930 when stainless steel became popular; these stainless steel wires have since remained the mainstay of orthodontics.[6,13] Stainless steel, as used in orthodontics, is usually either AISI 302 or 304. AISI 302 is the basic type with 18 percent chromium, 8 percent nickel and .15 percent carbon with type 304's main difference being that carbon is limited to .08 percent. Both 302 and 304 are classified as 18-8 stainless steels. The 300 series of steels cannot be hardened by heat treatment but are readily hardened by cold working.[11]

As material technology progressed, chromium-cobalt alloys were developed. Elgiloy, developed by the Elgin National Company for watches, is one of these chromium-cobalt alloys which has been utilized in orthodontics. Elgiloy is made of eight materials (40% cobalt, 20% chromium, 15% nickel, 7% molybdenum, 2% manganese, .04% berylium, .15% carbon, and 15.81% iron).[3,4] Another wire, Multiphase MP35N, has similar composition to Elgiloy and is made of 35% cobalt, 35% nickel, 20% chromium, 10% molybdenum. Other elements that can either be intentially added or present as residuals of melting include a maximum of: 1% iron, 1% titanium, 0.025% carbon, 0.15% manganese, and 0.15% silicon.[6]

Nitinol wire emerged from the search for a wire with lighter forces and greater working range. William Buehler, a research metallurgist with the U.S. Navy, invented Nitinol in the early 1960's.[1,9] Clinically, orthodontic use of Nitinol took advantage of its most unique property, its resistance to taking a bend.[1] The original alloy contained 55% nickel and 45% titanium while the commercially available Nitinol orthodontic wire now contains 52% nickel, 45% titanium, plus 3% cobalt.[2,9] Nitinol has the disadvantage of not being able to take desired bends and loops and will break when bent over a sharp edge.[1,9]

Beta titanium, used as a structural metal since 1952, is now being introduced into the orthodontic field and has great promise due to its high maximum elastic deflection. Pure titanium, at tempertures above 1,625°F, rearranges into a body-centered cubic lattice (beta phase) which can impart the unique properties of high springback and formability with low stiffness. When molybdenum or columbium are added, the titanium alloy can maintain this beta phase even when cooled to room temperature.[2] The Beta III phase, used by Ormco in their TMA wire, was developed by the Crucible Steel Company in the late 1950's. The composition ultimately was developed and its processing further studied under Air Force sponsorship. The outstanding cold formability inherent within this beta alloy was of major interest. Goldberg and Burstone showed that the formability of beta titanium was similar to stainless steel when measured by the ADA cold-bend test.[5]

The purpose of this paper is to evaluate five orthodontic wires by calculating and comparing their modulus of elasticity, .2% yield strength, ultimate tensile strength, percentage elongation, and maximum elastic deflection ($\frac{ys}{me}$).

Terms Defined

MAXIMUM ELASTIC DEFLECTION - ratio of yield strength divid-by elastic modulus; also known as springback.[5]

MODULUS OF ELASTICITY - ratio between unit stress and unit strain, usually expressed as pounds per square inch; an index of stiffness.[12]

PERCENTAGE ELONGATION - ratio of increase in length after fracture to the original guage length.[12]

RANGE - a measure of how far a wire or material can be deformed without exceeding its elastic limit.

STIFFNESS - a measure of resistance to deformation, a measure of the force required to bend a wire a definite distance; has no relationship to maximum force or distance that can be sustained.

STRENGTH - a measure of maximum possible load, or greatest force a wire can sustain when it is loaded to its limit or fracture point.

ULTIMATE TENSILE STRENGTH - the maximum load that a wire can withstand at fracture divided by the cross sectional area.

YIELD STRENGTH - represents a stress slightly higher than the proportional limit (point at which plastic flow begins), usually specified as a percent yield strength representing a percent deviation in strain from the linear portion of the stress strain curve.

METHODS AND MATERIALS

Five types of orthodontic wires (.017 x .025") were chosen for testing:

1 - stainless steel (type 304) - Unitek

2 - Multiphase MP35N - American Orthodontics

3 - Blue Elgiloy - Rocky Mountain Orthodontics

4 - Nitinol - Unitek

5 - beta titanium (TMA) - Ormco

Fifteen samples, in the "as received" condition, of each type of wire were tested on a Riehle Modle FS-5 Universal Screw Power Testing Machine (Fig. 1). In conjunction with the FS-5, a Riehle Model DN-20 extensometer (Fig. 2) and a Riehle Model RD-5 chart recorder (Fig. 3) were used. After each sample was engaged in the jaws of the FS-5 and the extensometer was placed onto the wire, the samples were pulled until fracture occured.

The FS-5 has six scale ranges of 50, 250, 500, 1000, 2000, 5000. The 50-pound scale was used during the initial phase of each test in order to obtain a more accurate measure of the slope of the stress/strain curve. Because fracture occured at a point beyond the 50-pound scale it was necessary to change to the 250-pound range during each test. This was done while the machine ran continuously and had no effect on the stess and strain being applied on the wire. The cross-head speed of the FS-5 was set at .1 inches per and the extensometer blades were set 2 inches apart giving

FIG. 1

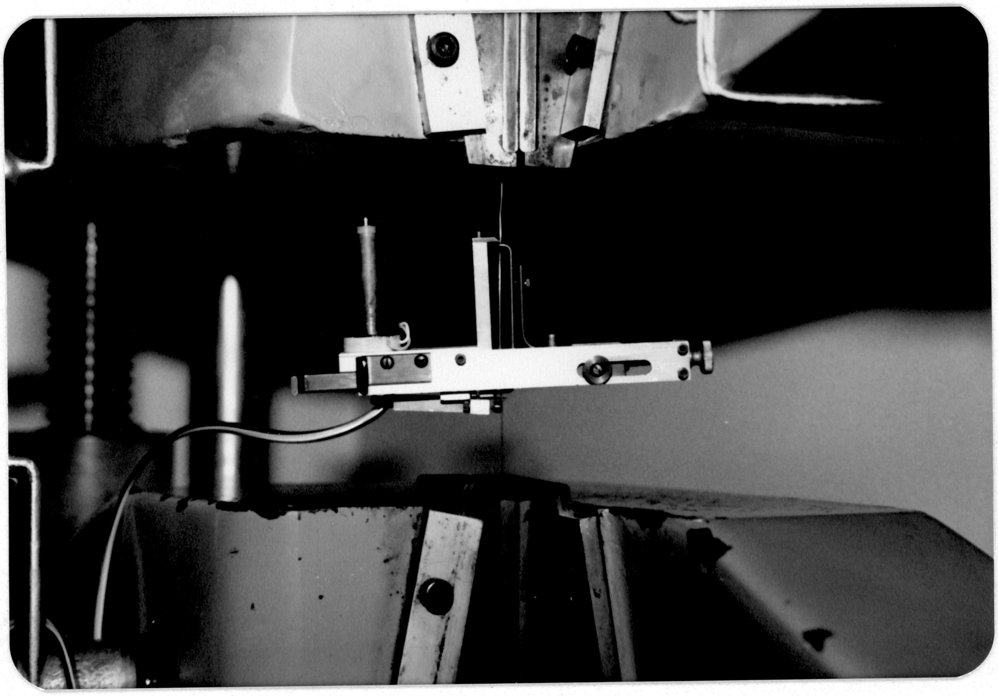

FIG. 2

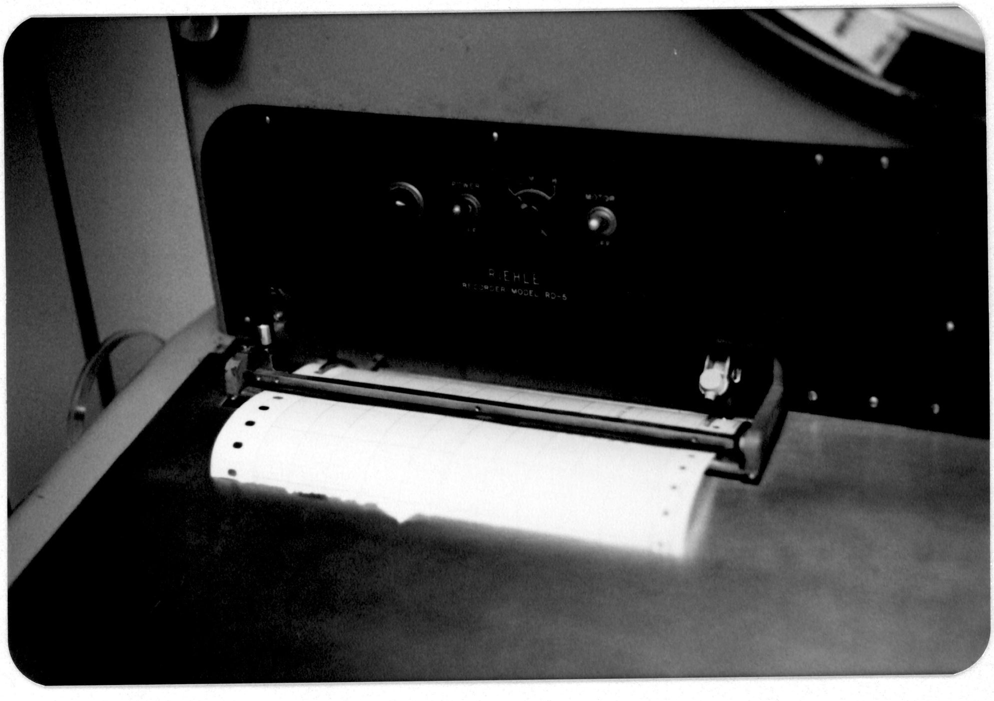

FIG. 3

it a range of .04". The chart recorder was set on the low range giving a magnification ratio of 250 to 1. With these particular settings each inch of chart paper (X axis) was equal to .004" elongation or .002 strain[10], and each division on the load (Y axis) was equal to 1% of the pound range being used. Three wires (stainless steel, Multiphase, and Blue Elgiloy) could all be tested within the .04" range of the extensometer while both beta titanium and Nitinol required multiple settings of this instrument in order to measure their percent elongation.

After completing the tests five properties were calculated from the stress strain curve: modulus of elasticity, .2% yield strength, ultimate tensile strength, percentage elongation, and maximum elastic deflection.

RESULTS

The tensile test has normally been used to determine the mechanical properties of orthodontic wire.[11] Fifteen samples of each of the five wire types were loaded until fracture. Since the specimens were slowly loaded along their long axis, and the load was plotted as a function of specimen extension[13], there is some question as to whether a tensile test is necessarily applicable to orthodontic situations. The results obtained within this test should be qualified with the knowledge that there are other stresses applied to orthodontic wires other than those of tensile quality.

From the resultant stress-strain curves five properties were obtained: 1) modulus of elasticity, 2) .2% yield strength, 3) ultimate tensile strength, 4) percentage elongation, and 5) maximum elastic deflection $\frac{ys}{me}$.

The results are listed in tables I - VI

Table I - stainless steel
II - Multiphase
III - Elgiloy
IV - beta titanium
V - Nitinol
VI - Mean and Standard Deviation Values (of all five wire types)

Fig. 4 shows the mean values for each wire plotted onto a stress/strain curve.

Table I
Stainless Steel

Test #	Modulus of Elasticity 10^6 psi	.2% Yield Strength 10^5 psi	Tensile Strength 10^5 psi	Percentage Elongation	YS/ME 10^{-3}
1	29.4	2.03	2.79	1.72	6.9
2	26.7	2.26	2.79	1.49	8.4
3	28.0	2.15	2.79	1.53	7.7
4	29.4	2.18	2.82	1.72	7.4
5	26.3	2.30	2.85	1.75	8.7
6	28.7	2.26	2.59	1.24	7.8
7	27.6	2.24	2.82	1.54	8.1
8	27.1	2.29	2.86	1.48	8.5
9	26.9	2.41	2.86	1.78	9.0
10	27.8	2.44	2.79	1.46	8.8
11	30.0	2.18	2.71	1.45	7.3
12	27.8	2.12	2.72	1.52	7.6
13	26.9	2.24	2.74	1.54	8.3
14	26.4	2.24	2.73	1.62	8.5
15	26.5	2.32	2.76	1.59	8.8

Table II
Multiphase

Test #	Modulus of Elasticity 10^6 psi	.2% Yield Strength 10^5 psi	Tensile Strength 10^5 psi	Percentage Elongation	YS/ME 10^{-3}
1	35.3	1.88	2.76	2.02	5.1
2	31.6	2.06	2.76	1,94	6.5
3	30.2	1.88	2.41	2.00	6.2
4	32.9	1.85	2.41	1.84	5.6
5	31.0	1.85	2.41	2.00	6.0
6	30.6	1.88	2.41	2.00	6.1
7	32.4	1.91	2.44	2.00	5.9
8	32.0	1.85	2.41	2.02	5.7
9	34.9	1.85	2.44	1.98	5.3
10	33.3	1.82	2.41	2.00	5.5
11	31.7	1.82	2.41	2.00	5.7
12	32.5	1.85	2.41	1.94	5.7
13	32.5	1.85	2.41	2.00	5.7
14	33.0	1.88	2.41	1.96	5.7
15	35.7	1.88	2.79	1.95	5.3

Table III
Blue Elgiloy

Test #	Modulus of Elasticity 10^6 psi	.2% Yield Strength 10^5 psi	Tensile Strength 10^5 psi	Percentage Elongation	YS/ME 10^{-3}
1	28.3	1.79	2.38	1.62	6.3
2	28.3	1.85	2.44	1.62	6.5
3	27.0	1.85	2.32	1.50	6.9
4	27.2	1.92	2.41	1.64	7.1
5	26.0	1.88	2.41	1.74	7.2
6	28.1	1.91	2.41	1.78	6.8
7	28.3	1.79	2.32	1.67	6.3
8	27.5	1.91	2.41	1.66	6.9
9	27.8	1.79	2.35	1.68	6.4
10	28.9	1.85	2.41	1.76	6.4
11	27.5	1.79	2.38	1.88	6.5
12	31.7	1.79	2.44	1.54	5.6
13	27.6	1.91	2.41	1.60	6.9
14	27.1	1.79	2.35	1.73	6.6
15	28.2	1.94	2.44	1.71	6.9

Table IV
Beta Titanium

Test #	Modulus of Elasticity 10^6 psi	.2% Yield Strength 10^5 psi	Tensile Strength 10^5 psi	Percentage Elongation	YS/ME 10^{-3}
1	11.5	1.21	1.82	3.30	10.5
2	11.5	1.21	1.79	2.84	10.5
3	11.5	1.24	1.82	3.59	10.8
4	12.3	1.35	1.79	2.64	11.0
5	10.9	1.18	1.79	3.81	10.8
6	12.0	1.35	1.82	2.48	11.3
7	11.4	1.29	1.82	3.36	11.3
8	11.4	1.16	1.79	2.96	10.2
9	11.4	1.35	1.82	3.07	11.8
10	11.5	1.18	1.76	2.76	10.3
11	11.6	1.29	1.82	2.83	11.1
12	11.3	1.19	1.76	2.88	10.5
13	11.3	1.24	1.82	2.86	11.0
14	13.2	1.18	1.82	2.53	8.9
15	12.2	1.29	1.82	2.83	10.6

Table V
Nitinol

Test #	Modulus of Elasticity 10^6 psi	.2% Yield Strength 10^5 psi	Tensile Strength 10^5 psi	Percentage Elongation	YS/ME 10^{-3}
1	6.01	.724	2.12	9.03	12.0
2	5.88	.706	2.12	8.52	12.0
3	5.63	.618	2.09	9.06	11.2
4	5.88	.606	2.09	8.74	10.3
5	5.35	.659	2.18	8.70	12.3
6	5.48	.694	2.18	8.70	12.7
7	6.09	.642	2.12	7.98	10.5
8	5.41	.771	2.11	7.62	14.3
9	5.69	.594	2.09	9.48	10.4
10	5.66	.659	2.12	8.54	11.6
11	6.27	.553	2.06	7.96	8.8
12	5.56	.576	2.06	9.32	10.4
13	5.98	.594	2.06	7.40	9.9
14	5.80	.624	2.12	8.70	10.8
15	6.02	.582	2.12	9.20	9.7

Table VI

Means and Standard Deviations

Wire Type	Modulus of Elasticity	.2% Yield Strength	Tensile Strength	Percentage Elongation	$\frac{Y.S.}{M.E.}$
Stainless Steel	27.7×10^6 (1.19)	2.34×10^5 (.106)	2.77×10^5 (.071)	1.56 (.141)	8.1×10^{-3}
Multiphase	32.6×10^6 (1.64)	1.87×10^5 (.057)	2.49×10^5 (.148)	1.98 (.046)	5.7×10^{-3} (.37)
Elgiloy (blue)	27.9×10^6 (1.25)	1.85×10^5 (.058)	2.39×10^5 (.041)	1.68 (.097)	6.6×10^{-3} (.40)
Beta Titanium	11.7×10^6 (.56)	1.25×10^5 (.068)	1.80×10^5 (.022)	2.98 (.380)	10.7×10^{-3} (.66)
Nitinol	5.78×10^6 (.27)	$.64 \times 10^5$ (.062)	2.11×10^5 (.037)	8.60 (.616)	11.1×10^{-3} (1.39)

MEAN STRESS/STRAIN CURVES

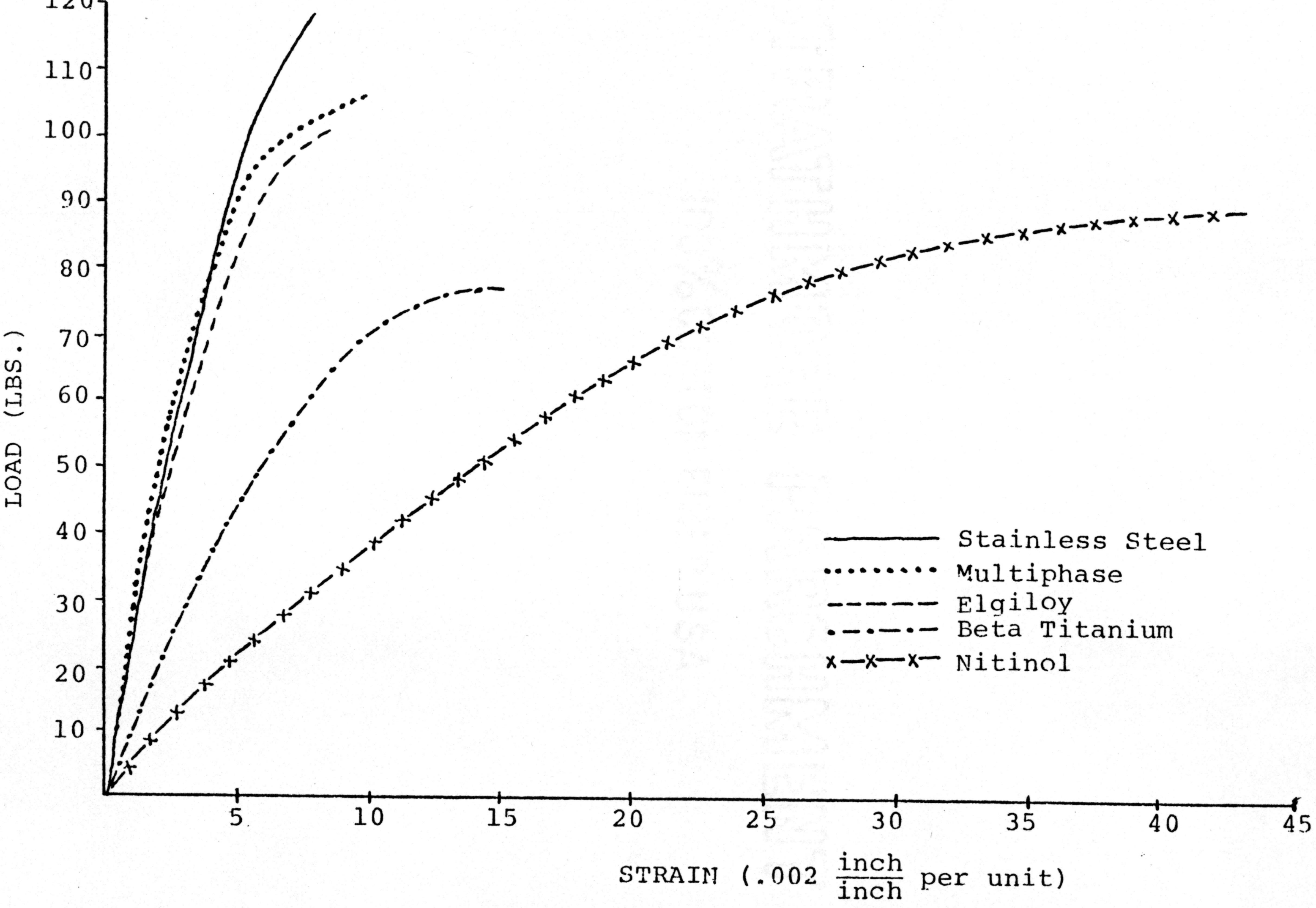

FIG. 4

DISCUSSION

Orthodontists depend upon the elastic properties of wire to store and then deliver forces to a tooth. A great deal of emphasis has gone into designing new wire loop systems so as to deliver lighter forces and allow a greater range of activation. Utilizing these loops the clinician was able to overcome some of the limitations of the material itself by incorporating greater length of wire between the teeth.

With recent advancement in material technology there is a broader spectrum of wire properties being offered to the clinician. These different properties should be of more then casual interest to the orthodontist.

In this study five separate properties were measured; 1) modulus of elasticity, 2) .2% yield strength, 3) ultimate tensile strength, 4) percentage elongation and 5) maximum elastic deflection $\frac{ys}{me}$.

Modulus of elasticity and .2% yield strength influence stiffness, strength, and working range in a wire and thus are probably the most applicable properties to orthodontics. The modulus of elasticity is an expression of the steepness of the elastic curve, and is and index of stiffness or resistance to stretching[12]. An important characteristic of the modulus of elasticity is that it is usually one of the most invariable physical properties of a metal. Heat treatments that soften or harden the metal have little effect on the modulus of elasticity[7,12]. The more that the stress/strain curve tends toward vertical, the larger the force required to stretch the wire. As modulus of elasticity increases, the stiffness of the sample increases and the range decreases.

Stainless steel and Elgiloy had similar values for modulus of elasticity while Multiphase had the highest modulus of elasticity value and can thus be considered the stiffest. Compared to stainless steel, beta titanium and Nitinol had one-half and one-fourth the modulus of elasticity values respectively. Thus a beta titanium wire would have to be deflected twice the distance of a stainless steel wire to produce an equal force, given both wires of equal dimensions.

As a wire is placed under tension it first exhibits elastic strain before showing any plastic strain (Fig. 5). If the load is released during elastic strain the wire will return to its original length. During this straight line portion of the curve the grains of the metal as well as the atoms within the grains shift only slightly; they do not move far enough to prevent the electromagnetic forces holding the atoms together from returning them to their original relationships when the force is released.[13]

The yield strength is the point at which plastic flow begins. Further increases in force beyond the yield strength will cause some atoms to reach a point where they can move to new positions as easily as they can return to their original positions and the material is more easily deformed. As some atoms shift to new positions the elastic curve begins

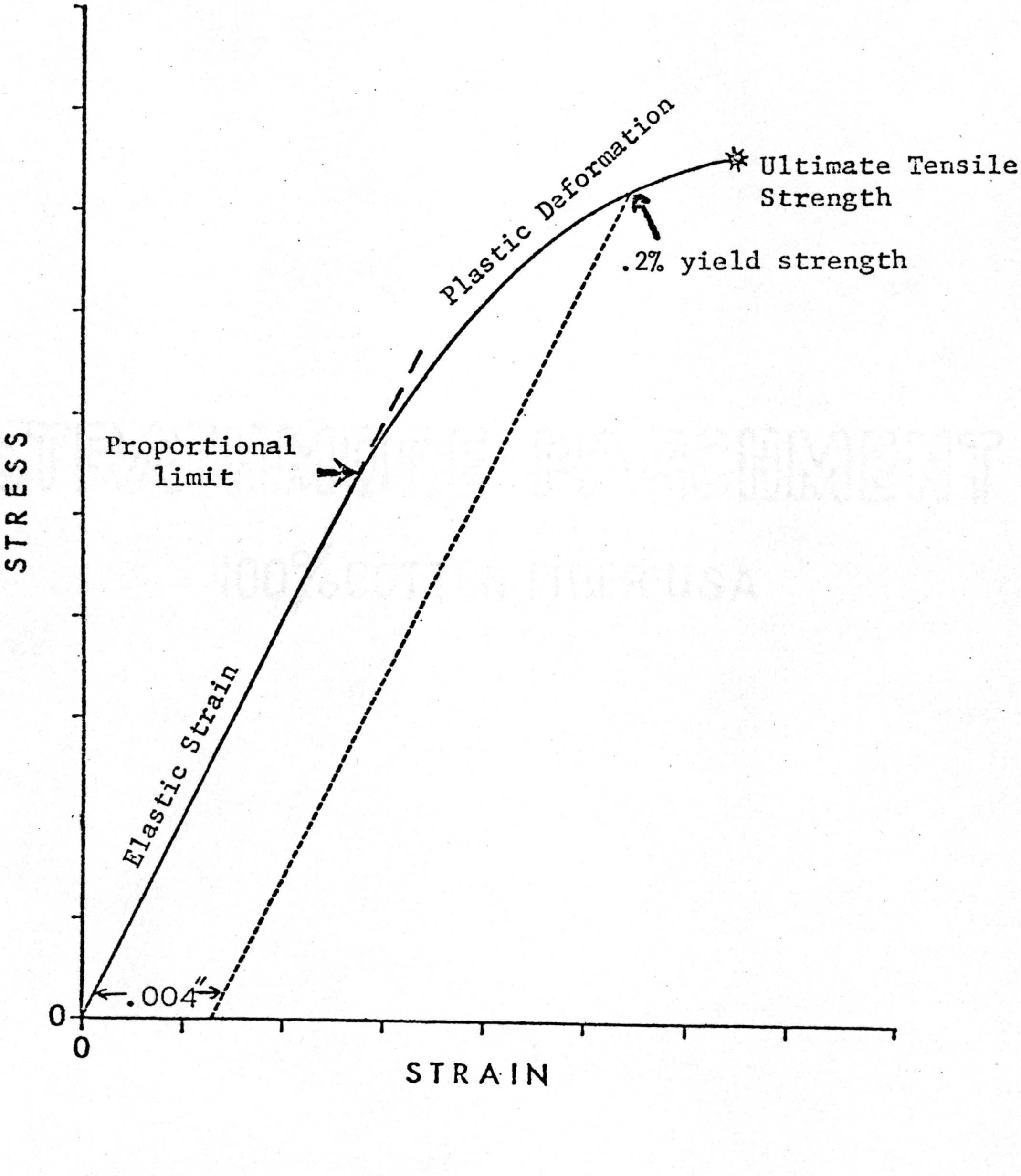
Plastic Deformation
Ultimate Tensile Strength
.2% yield strength
Proportional limit
Elastic Strain
STRESS
.004"
0
0
STRAIN

FIG. 5

to deviate to the right.[12] At this point the metal has undergone a permanent change and will no longer return to its original form when the stress is released.[8] The permanent change is called plastic deformation. Since most materials do not show a clear-cut point at which plastic flow begins, but rather a gradual change from elastic to plastic behavior, it is difficult to identify an exact yield strength point. A common method of determining yield strength is to determine a point on the stress/strain curve equivalent to .2% strain.[7] When a line is drawn parallel to the elastic part of the stress/strain curve at .2% strain offset an intercept point of two lines becomes the .2% yield strength.

Yield strength has a direct relationship on strength and range; the greater the yield strength the greater the strength and range of the wire. Stainless steel exhibited the highest .2% yield strength with a value of 2.24×10^5psi and Nitinol had the lowest value at 6.4×10^4psi. Both Multiphase and Elgiloy had similar values at 1.87×10^5psi and 1.85×10^5psi respectively while beta titanium possessed a yield strngth of 1.25×10^5psi, almost twice that of Nitinol.

Ultimate tensile strength does not correspond to stiffness, strength, or range but rather gives the maximum load that will cause a wire to break. It is the maximum resistance to fracture divided by the cross-sectional area. All wires tested were of .017 x .025" cross-section. It is important to remember that in manufacturing of wire it is found that the finer the wire, the higher will be the tensile strength.

This is due to the relative depth of the plastic deformation, during drawing of the wire through a die, causing pressure to be applied to the outside surface of the wire, while its center core is least affected.[14]

Stainless steel had the highest tensile strength while Multiphase, Elgiloy, and Nitinol had similar but somewhat lower values. Beta titanium had the lowest value for the five wires tested. Since most fractures in orthodontic wire occur from a shear stress or from cold working, it is important to keep in mind that ultimate tensile strength failure may not occur in clinical use.

Percent elongation was calculated by dividing the total amount of strain at fracture by the original length and multiplying by 100. This property gives an indication of the ductility of a wire. When a wire is stressed beyond its proportional limit, it becomes permanently deformed. If the wire can withstand considerable permanent deformation without rupture, it is said to be ductile. Ductility, which is dependent upon plasticity and tensile strength, is the ability of a material to withstand permanent deformation under a tensile load without rupture.[11]

Nitinol had the highest percentage elongation (8.6%) and stainless steel had the lowest (1.56%). Beta titanium had a comparitively high value of 2.99% while Multiphase and Elgiloy had values of 1.98% and 1.68% respectively. This points out that Nitinol is very ductile because of its ability to withstand considerable permanent deformation without rupture.

Springback, or maximum elastic deflection, was calculated from the ratio of yield strength divided by the elastic modulus. The yield strength used was the .2% offset yield strength. Goldberg and Burstone pointed out that this ratio is a good predictor of the maximum deflection of an orthodontic wire[5]; higher values allow increased activation, which is desirable unless other properties such as formability are sacrificed excessively. Multiphase had the lowest springback ratio of 5.7×10^{-3} due to its very high modulus of elasticity. Nitinol had the highest ratio value of 11.1×10^{-3} with beta titanium slightly lower at 10.7×10^{-3}. Orthodontic appliances with low load deflection rates and high elastic deflections have distinct clinical advantages according to Goldberg. They were: (1) the ability to apply lower forces, (2) a more constant force over time as the appliance experiences deactivation, (3) greater ease and accuracy in applying a given force, and (4) the ability to use larger activations and the associated increased working time of the appliance. Both beta titanium and Nitinol have these low load deflection rates and high elastic deflections.[5]

SUMMARY AND CONCLUSION

Tensile properties were obtained and compared between five types of wires; stainless steel, Multiphase, Blue Elgiloy, beta titanium, and Nitinol. All wires were of .017 x .025" dimension and were tested until fracture so as to obtain five tensile properties; 1) modulus of elasticity, 2) .2% yield strength, 3) ultimate tensile strength, 4) percentage elongation, and 5) maximum elastic deflection. Having used the same calibrated tensile tester on all the wires of equal dimension it was possible to compare the results of one wire to another.

The tests showed that Multiphase had the highest or stiffest modulus of elasticity value while stainless steel and Blue Elgiloy had very similar but lower values. Beta titanium had less than one-half and Nitinol less than one-fourth the modulus of elasticity than that of stainless steel. Stainless steel showed the highest yield strength and tensile strength, while the lowest yield strength was that of Nitinol and the lowest tensile strength that of beta titanium. Stainless steel possessed the lowest percentage elongation while Nitinol had the highest, more than five and one-half times that of stainless steel. For maximum elastic deflection Multiphase had the lowest value while beta titanium and Nitinol were the highest.

In general, stainless steel, Multiphase and Elgiloy (in the "as received"condition) had very similar properties. The forces they would produce would vary more upon the dimensions of the wire than upon the type of wire chosen. Both beta titanium and Nitinol have properties that differ a great deal from the other three wires.

Since the elastic modulus of a stainless steel wire is approximately twice that of beta titanium, the stainless steel wire will exert twice as much force on the tooth as will a beta titanium wire of the some cross sectional area when each is activated by bending to the same angular deflection. Conversly, a smaller stainless steel wire can be employed to exert the same force as a larger beta titanium wire.

It is apparent that there are some striking differences in physical properties between some wires currently available to the clinician. As the orthodontist obtains a better working knowledge of the materials he is using and the properties that are inherent within them he may then be better able to select those wires which will give him the most desired results.

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