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AN EVALUATION OF WIRES FOR ORTHODONTIC LINGUAL EXPANSION ARCHES

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A Thesis submitted in partial requirement for the degree of
Master of Dental Science

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CHAPTER 1

1. INTRODUCTION AND HISTORY

The purpose of this research is to compare the mechanical properties, spring rate and proof load, of a nickel base alloy wire - Nimonic 90, with the following materials:

(1) Stainless Steel Wire
(2) Cobalt Chromium Wire
(3) Platinised Gold Wire

when bent in a structural form similar to that of the upper lingual expansion arch, and to consider which of these materials is the most suitable for this type of orthodontic appliance.

Anderson (1) in his textbook "Practical Orthodontics" attributes to Pierre Fauchard in 1723 the idea of the orthodontic expansion arch, and gives the history and development of several types of expansion appliances; such as those of:

(a) Westcott, (1859) who used a double clasp on either side of the dental arch and a wire across the palate for lateral expansion.
(b) Farrar, who classed a number of appliances as "jacks", some of which were only used for moving teeth that were inclined towards one another, and depended on this inclination for retention of the appliance, and others which were anchored in various ways by making use of the elasticity of metal, screws, ligatures, clasps or bands.
(c) W.H. Coffin, who in 1881 introduced the coffin plate, which consisted of a divided vulcanite plate, the two halves being connected by a piece of piano wire bent to the shape of the letter W. The appliance was held in place by either caps or clasps on the molars and by means of the spring in the wire, exerted lateral pressure, or expansion force.

(d) V.H. Jackson who developed a system of appliances which combined an improved "crib" with a modification of the W-shaped wire as used by Coffin.

The lingual, or butterfly lingual expansion arch in use today normally consists of a wire bent to a W shape attached to orthodontic bands in the molar or pre-molar region. Some examples of this type of appliance are given in Figures (i), (ii), (iii), (iv). (1).

The appliance is activated by expanding the arch form beyond its proportional limit and it is then inserted under compression resulting in a lateral expansive force.

The W-shaped spring is normally attached to the orthodontic bands by silver soldering, although other methods of attachment are occasionally used, e.g. the wire can be bent so that it fits into a slot on the lingual of the band and the spring can then be removed without dislodging the bands. However the soldered appliance is normally used; it is easier to fabricate
Figure 1. (i)

Upper Lingual Expansion Arch
Figure 1. (ii)

Upper Lingual Expansion Arch
Figure 1. (iii)

Upper Lingual Expansion Arch
Figure 1. (iv)

Upper Lingual Expansion Arch
and appears to offer greater directional control of the lateral forces exerted by the appliance. Wires of platinised gold, stainless steel and more recently cobalt chromium, are usually used for the W spring of this appliance.

Wires of various alloys have been used for the W springs of expansion arches, and since the introduction of stainless steel wire to orthodontics, around 1930, (Gaston)\(^{25}\) many comparisons have been made between precious metal and stainless steel for orthodontic purposes.

The early expansion appliances usually used a spring of piano wire, as in the Coffin Plate (Anderson)\(^{1}\) or a precious metal alloy spring, (Pollock\(^{41}\), Eby\(^{23}\)). H.C. Pollock\(^{41}\) advocated the use of gold plated tungsten wire, as, "the elastic content of tungsten being about twice that of platinum, its stiffness about six times that of 30% iridium in platinum, also the quality that it does not anneal or lose its stiffness and elasticity at tremendous heat, makes it particularly adaptable for some of the uses of the orthodontist". The chief objections, then, to this wire were its brittleness "it had to be cut or etched with a knife - edged stone and then broken like glass - and its unreliability in large sizes".

Dewey (1923)\(^{21}\) advocated the use of spring gold and platinum wire for removable orthodontic appliances "as it is a desirable
material from which to obtain spring force".

Williams (1923)(69) compared various gold wires using piano wire as a standard and attempted to translate the desirable orthodontic properties of wires into actual tangible figures of strain or stress. He designed an instrument to determine the suitability or not of orthodontic wires which was based on the "elasticity" of the material tested.

Brumfield (1930)(11) gave an interpretation of the desirable properties of finished orthodontic structures from the published test results of individual gold alloys. He calculated values of load and deformation of various auxiliary springs of gold wires.

De Coster (1932)(18) began using stainless steel in orthodontics in 1924. He advocated stainless steel for bands, auxiliaries and arches, and felt that great progress in the use of rustless steel was made by the use of electric welding.

Simon (1933)(51) used rustless steel for his lingual spring beam apparatus and considered that "very probably rustless steel will be the material of the future".

Paffenbarger et al (1943)(40) credit Frederick Hauptmeyer, chief of the Krupp Dental Clinic in Essen, Germany, as the first user of stainless steel for oral appliances. They felt that stainless steel compared very favourably with gold alloy wires as an orthodontic spring material. However gold had one definite advantage in that it could be hardened by heat treatment after
appliance construction.

Angell (1950)\(^{(3)}\) compared 18 - 8 stainless steel wire with platinised gold wire, using tensile and bend tests, for orthodontic arches and springs and concluded that "gold alloy wires will serve orthodontists for arches and springs better than the best stainless steel wires. The advantages of gold alloys which can be heat treated after soldering is especially pronounced as compared with stainless steel".

Steiner (1953)\(^{(56)}\) considered the physical qualities of stainless steel and precious metal and concluded that while both have advantages and are useful for orthodontic purposes, precious metal is the most suitable for orthodontic purposes.

Gerber (1964)\(^{(26)}\) described a butterfly expansion appliance in which he used a spring of cobalt chromium (Blue Elgiloy) wire.

Craig et al (1965)\(^{(16)}\) compared 17 - 7 precipitation - hardenable stainless steel, with 18 - 8 stainless steel and cobalt nickel wires used in orthodontics, and concluded that while the properties of the 17 - 7 precipitation hardenable stainless steel in the cold worked martensitic condition were comparable to those of the 18 - 8 stainless steel and cobalt chromium nickel wires examined, the material had no significant advantages over 18 - 8 stainless steel for orthodontic use.
Mahler and Goodwin (1967)(33) compared elastic deformation - force ratios and elastic force limits of small diameter orthodontic wires of stainless steel and cobalt chromium from different manufacturers when bent into loops of various configurations. They gave no details of wire diameters and wire configurations were bent with pliers. They concluded that of the types, designs, and conditions tested all produced elastic force limits in excess of that apparently required of the light wire applications and that heat treatment increased the elastic force limit appreciably in most cases but decreases slightly the elastic deformation - force ratio.

Howe et al (1968)(29) compared the effects of stress relief for types 302 and 316 austenitic stainless steel orthodontic wires. They found sizeable variations in mechanical properties from batch to batch of the same wire of the same grade. They concluded that the type 316 material examined exhibited superior elastic properties compared to the type 302, but that both types needed a stress relief anneal to give maximum stiffness and resistance to deformation.

The reason for suggesting that the nickel-base alloy chosen (Nimonic 90) may be suitable for this type of appliance are:-(a) As supplied in wire form the alloy is relatively ductile and appliances should be able to be constructed quickly and accurately.
(b) The alloy has a high ultimate tensile strength and proportional limit after hardening.

(c) The alloy can be aged over a wide range of temperatures, 300° - 800° C, without seriously affecting its mechanical properties.

The materials used for comparison were (nominal diameter 0.036 in.)

1. Platinised Gold wire (Ney Oro - Elastic 12)
2. Stainless Steel wire (Remanit Denta"rum)
3. Cobalt Chromium Alloy wire (Elgiloy Yellow)
   (Elgiloy Blue)

The reasons for selecting these wires for comparison were:

1. **PLATINISED GOLD WIRE**
   (a) It is often used for this appliance.
   (b) It has a low modulus of elasticity compared with stainless steel.
   (c) It has a high proportional limit after ageing (for a precious metal alloy).
   (d) It can be age hardened after fabrication of appliances and the process is reversible and repeatable.

2. **STAINLESS STEEL WIRE**
   Stainless steel wire is widely used in orthodontics and is used for this appliance. The proportional limit can be increased by work hardening and heat treatment.

3. **CHROMIUM COBALT WIRE**
   (a) It is recommended and widely used for this type of appliance.
(b) It can be heat treated after fabrication of appliance.
Two forms of this wire were used for comparative purposes,
these were Yellow Elgiloy - designated cobalt chromium Y
and Blue Elgiloy - designated cobalt chromium B. The
distributor(44) describes Yellow Elgiloy as being ductile,
and Blue Elgiloy as being soft.

The upper lingual expansion arch uses the elastic properties of
wire to deliver the forces derived from the appliance.

To present the theoretical principles involved it is necessary
to consider
(a) The Elasticity and Strength of Materials ..... Chapter 2
(b) Structural Interpretation of Physical Properties
of Materials ........................................ Chapter 3
(c) Mechanical Springs ................................. Chapter 4

All definitions unless specifically stated otherwise are taken
from Metals Handbook 8th Edition.(34)
CHAPTER 2

2. ELASTICITY AND STRENGTH OF MATERIALS

2.1. STRESS, STRAIN AND ELASTICITY (SALMON) (45)

2.1.1. ELASTIC MATERIAL. When making an analytical study of the effect on a body of distorting forces, it is customary to assume that the material of which the body is composed is perfectly elastic. That is to say, it is assumed that not only do all effects of the distorting forces immediately disappear on removal of those forces, but that the distortion produced in the material is proportional to the magnitude of the effort which gives rise to it. It is further assumed that the material has the same elastic properties in every direction. Such material is called isotropic material. No engineering material completely satisfied this ideal, but many approximate closely if the distortion produced be not too great. The theory given below can be safely applied to these materials provided that the stress produced at any point does not exceed the elastic limit. This limit is discussed in 2.1.5.

2.1.2. TENSILE STRESS AND STRAIN. Suppose that a bar of length 1 be subjected to two longitudinal forces \( F \) \( F \), directed along its axis, as shown at (i) Figure (2). Careful measurements will show that, as a result, the bar has lengthened by a certain amount, which will be denoted by \( S_1 \). This alteration in length \( S_1 \) is called the extension produced by the forces \( F \) \( F \).
Figure 2. Forces on a Longitudinal Bar.

Figure 3. Shear Forces on a Rigid Bar.
The ratio \[ \frac{\text{extension}}{\text{original length}} = \frac{\delta l}{l} = S \quad \ldots \ldots \quad (1) \]
is termed the strain. Evidently the strain is the alteration of length per unit length of the bar, for if \( l = 1 \), \( S = \delta l \).

Owing to the action of the external forces \( F \), internal molecular forces, or stresses, will be set up in the material of the bar; and at any cross-section such as \( KK \) (ii, Figure 2), if the area be \( a \) and the intensity of molecular force or stress produced be \( f \) per unit area, it is evident that for equilibrium \( F = af \); or \( f = \frac{F}{a} \quad \ldots \ldots \ldots \ldots \quad (2) \)

By the expression stress, therefore, is to be understood the intensity of internal force called into play by the external forces. This intensity is expressed as units of force per unit of area. Since, in the example under consideration, the chief deformation produced is an extension, the bar is said to be in tension, the stress is called tensile stress, and the corresponding strain a tensile strain.

In elastic material the ratio of stress to strain is a constant, a relation known as Hooke's Law, after its discoverer. This ratio is called the modulus of elasticity. Hence,

\[ \frac{\text{stress}}{\text{strain}} = \frac{f}{S} = f. \frac{1}{\delta l} = \text{constant} = E \quad \ldots \ldots \quad (3) \]

where \( E \) is the tensile modulus of elasticity, often called Young's modulus.
It follows, therefore, that

$$\frac{f}{E} = \frac{F}{Ea} = \frac{\Delta L}{L}; \text{ or, } \Delta L = \frac{FL}{Ea} \quad \ldots \ldots \quad (4)$$

The magnitudes of $f$ and $E$ must be expressed in the same units, i.e. pounds per square inch. The value of the modulus of elasticity is different for different materials.

The above equations are strictly true if the stress over the cross section be uniform. If, as is often the case, the stress is not uniformly distributed, eq. (2) expressing the intensity of stress at any point must be written $f = \frac{\delta F}{\delta a}$, where $\delta F$ is the amount of the molecular force on an indefinitely small area $\delta a$.

Alternatively, in such a case as Figure (2), $f$ in eq. (2) may be regarded as the average stress over the cross section.

Young's Modulus or the modulus of elasticity is a measure of stiffness or rigidity, the higher its value, the greater the stress needed to produce a given deformation and the stiffer the material.

2.1.3. COMPRESSIVE STRESS AND STRAIN. If the direction of application of the forces $F$ be reversed, the bar will be in compression instead of tension (iii, Figure 2). The alteration of length will be a contraction instead of an extension, and the stress and strain produced will be a compressive stress and compressive strain respectively. The ratio of compressive stress to compressive strain will be the compressive modulus of elasticity, which may be taken as equal to $E$, the tensile
modulus. The same relation and equations will hold for
compressive stress and strain as for tensile - in fact one
may be regarded as a negative form of the other.

Pure tensile and compressive stresses and strains are sometimes
called simple stresses and strains, for any state of stresses
and strain can be reduced to combination of such simple stress
and strains.

2.1.4. SHEAR STRESS AND STRAIN. Suppose A B C D to be a
projecting length 1 of a body rigidly held at A D and acted on
by force F at B, as shown in Figure (3). It will be assumed
that the length 1 is so short that the bending set up is negligible.
Under the action of the force F the body will deform the rectangle
A B C D becoming the parallelogram A B' C' D'. This kind of
deformation is called shearing, and the angle B A B' = δφ,
which is a measure of the deformation, is called the shear strain.
The angle δφ is expressed in radians, and, since it will be very
small, δφ = \frac{B' B}{A B} . If a be the cross-section of the body,
the average intensity of the shear stress is \( f_s = \frac{F}{a} \); and,
as in the case of tensile and compressive stress and strain,
it is found that, in elastic material, the ratio of shear
stress to shear strain is constant. Hence,

\[
\frac{\text{Shear stress}}{\text{Shear strain}} = \frac{f_s}{\delta \phi} = \text{constant} = G \quad \ldots \ldots \ldots \quad (5)
\]
or, \( \delta \phi = \frac{f_s}{G} \), where G is the modulus of elasticity in shear,
often called the modulus of rigidity, a quantity corresponding
to the tensile modulus $E$, but not equal to it.

Eq. (5) may be written

$$\frac{f_s}{G} = \frac{F}{G a} = \sigma \phi = \frac{\sigma_y}{1}$$  \hspace{1cm} (6)

where $BB'$ is denoted by $\sigma_y$.

2.1.5. THE STRESS - STRAIN RELATIONSHIP. The stress - strain relationship is described in many textbooks on engineering, materials and structures, physics and dental materials. Earnshaw (22) gives as a convenient example of stress - strain relationship, a wire in tension Figure (4). Assuming the wire is made of some non-ferrous metal. If it is loaded gradually in small increments, and if measurements are made of the extension produced by each increment, then a series of readings can be obtained, of load against extension, right up to the breaking load.

Knowing the original cross sectional area of the wire, loads can be converted to stresses and similarly, from the original length extensions can be converted to strains. The results obtained from loading the wire enable us to plot stress against strain for each load increment, and so draw a stress - strain curve for that material. A typical stress - strain curve for the material specified is shown in Figure (5). From a stress - strain curve like this we can define many properties which are important in consideration of metals and alloys under load.

The first part of the stress - strain curve, $0A$ in Figure (5) is substantially a straight line. The material is obeying
Figure 4. Wire in Tension.

Figure 5. Typical Stress-Strain Curve.
Hooke's Law, and its behaviour is elastic. We call OA the elastic range; stresses in this range are elastic stresses; and we can say that only elastic deformation has taken place. If the load is removed at any time in the range OA, to all intent and purpose the strain returns to zero. If loads are re-applied, the new stress-strain curve follows the original one (i.e. the material is elastic).

Beyond the point A, the relationship between stress and strain is no longer linear, Hooke's Law no longer applies, and the behaviour of the material is no longer elastic.

The point A is called the proportional limit or the elastic limit.

Proportional limit can be defined as the maximum stress at which stress is directly proportional to strain.

Plastic deformation is occurring in the range A - B, but elastic strain is still present. If the load is removed at some stage in the plastic range, elastic recovery or "spring back" occurs, e.g. in Figure (6), if the load is removed at C the material recovers along the line C - D, parallel to the original elastic section OA. Thus, after the load is removed there is still some strain present, measured by OD; this represents the plastic deformation performed in the section A - C of the stress strain curve and is called permanent set, and is defined as the plastic deformation that remains upon releasing the stress that produces the deformation.
Figure 6. Stress-Strain Curve, Plastic Deformation.

Figure 7. Stress-Strain Curve, Proof Stress.
If the material is then reloaded; the unloading curve is retraced from D to C. After the point C is reached the stress strain curve continues along C - B, just as if the original loading had not been interrupted.

2.1.6. ELASTIC LIMIT. The elastic limit is the maximum stress to which a material may be subjected without any permanent strain remaining upon complete release of stress. Salmon\(^{(46)}\) states that the term "elastic limit" has been very loosely employed. It is sometimes used to denote -

(i) the limit within which the deformation entirely disappears when the load is removed;

(ii) the limit below which the elongation is proportional to the load;

(iii) the yield point, or as it is often called, the "commercial elastic limit".

In recent years (iii) is usually called the proportional limit. In mild steel is differs very little from (i). Very refined measurement, however, has shown that materials are only perfectly elastic under very low loads, for most materials very early develop minute permanent sets. Some experiments have given very low values for the elastic limit; but the term "proportional limit" is usually used to denote the point at which marked divergence from proportionality first appears. To avoid confusion it is better to speak of the "proportional limit" and "yield point", and not to use the terms "elastic limit" and "commercial elastic limit".
2.1.7. YIELD POINT. The yield point is the first stress in a material, usually less than the maximum attainable stress at which an increase in strain occurs without any increase in stress. Only certain metals exhibit a yield point. If there is a decrease in stress after yielding, a distinction may be made between upper and lower yield points.

2.1.8. YIELD STRESS. (Earnshaw)\(^{(22)}\). In order to get reproducible results, the stress is determined which produces a small, definite plastic strain. This will be a definite fixed point on the stress – strain curve, irrespective of how sensitive the measurements are. In effect, we select a very small but easily measurable plastic strain and say that any plastic deformation less than this is not serious. There are two common methods of assessing yield stress.

(a) The load is added in equal increments, and the stress noted at which increment first causes a strain twenty five per cent greater than the strain caused by that increment at the beginning of the test.

(b) The stress – strain curve is plotted as usual, and then a point is found on it corresponding to a definite plastic strain or permanent set of 0.001, i.e. of 0.1%. The stress necessary to produce this permanent set of 0.1% is called the 0.1% proof stress. It is easily found by drawing what is called an offset line on the stress – strain curve. (Figure 7).
In this case the offset line starts from a strain of 0.001 and is drawn parallel to the straight line part of the stress-strain curve. The point where it intersects the stress-strain curve corresponds to a permanent set of 0.001 (or 0.1%), and the stress at that point is the 0.1% proof stress. Sometimes a 0.2% proof stress is determined instead of 0.1%, or sometimes a smaller permanent set is defined, e.g. 0.02% or even 0.01%. Thus, there are two ways in which the yield stress can be measured. Both methods give similar results, since both are based on finding the stress which causes a small but easily measured plastic strain.

YIELD STRENGTH or YIELD STRESS. Can be defined as the stress at which a material exhibits a specified deviation from proportionality of stress and strain. An offset of 0.2% is used for many metals.

2.1.9. PROOF STRESS. Can be defined as:

(1) The stress that will cause a specified small permanent set in a material.

(2) A specified stress to be applied to a member or structure to indicate its ability to withstand service loads.

2.1.10. ULTIMATE TENSILE STRENGTH. Is the maximum conventional tensile stress that a material can withstand. Billberg(6) suggested that hard drawn stainless steel wires should have a proportional limit of eighty five per cent of their tensile strength. For springhard (high) tensile wires, ninety per cent is suggested.
Delgado and Anderson\(^{(19)}\) in tests on 18 - 8 stainless steel wires found that reverse bend tests gave some correlation to the ratio of proportional limit and ultimate tensile strength.

Wilkinson\(^{(66)}\) in his work with stainless steel wires of different diameters, and from different manufacturers found that two important points emerged from the consideration of proportional limit and tensile strength. These were:

1. Tensile strength increases as the diameter of the wire is reduced, drawing conditions being equal. (This phenomenon is probably due to the relative depth of the plastic deformation, as the process of drawing causes pressures to be applied to the surface of the wire, its central core being the area least affected).

2. Tensile strength cannot be used as a reliable measure for proportional limit.

Manufacturers tend to supply strength data only, since it is much easier to determine tensile strength than proportional limit for wires.

2.1.11. DUCTILITY. Ductility is the ability of a material to deform plastically without fracturing, being measured by elongation or reduction of area in a tensile test or by other means.

Salmon\(^{(47)}\) stated that one way of assessing ductility is to measure the total strain at fracture as a percentage and this gives the percentage elongation and gives an idea of the relative
ductilities of different materials.

2.1.12. TOUGHNESS. Toughness is the ability of a metal to absorb energy and deform plastically before fracturing. It is usually measured by the energy absorbed in a notch impact test (Salmon)\(^{(48)}\), but the energy under the stress-strain curve in tensile testing is also a measure of toughness. (Metals Handbook)\(^{(34)}\)

If the amount of energy involved is large the material is tough. If the energy is small the material is brittle (Earnshaw).\(^{(22)}\)

2.1.13. BRITTLENESS. Britleness is the property of a material that permits crack-propogation without appreciable plastic deformation.

2.1.14. HARDNESS. Hardness is the resistance of metal to plastic deformation usually by indentation. However, the term may also refer to stiffness or temper, or to resistance to scratching, abrasion or cutting. Indentation hardness may be measured by various hardness tests, such as Brinell, Rockwell and Vickers, (Skinner, Salmon).\(^{(52)},(48)\)

There appears to be a direct relationship between the ultimate tensile strength and the Brinell hardness number, such that the ratio of these quantities is approximately constant. (Salmon)\(^{(48)}\)

Wilkinson\(^{(67)}\) tested a specific 18 - 9 austenitic stainless steel orthodontic wire and found that for the range of temperatures
and times selected the hardness of the wire was directly proportional to the tensile strength. For gold alloys it has been found that the Brinell Hardness number is directly proportional to the proportional limit and to the ultimate tensile strength (Bush, Taylor and Peyton). (15)

2.1.15. BEAMS. (Earnshaw) (22) A simple beam is one supported at each end, and loaded in the centre. (Figure (i) 8)

When a simple beam bends, there will be a neutral layer where the stress is zero. This can be imagined as an infinitely thin, horizontal layer through the centre of the beam. All parts of the beam below the neutral layer will be in tension, and all parts above the neutral layer will be in compression.

In both cases, the stress increases with the distance from the neutral layer, and is at a maximum on the surface. In addition to those longitudinal stresses, shear stresses are set up as well, as a result of shear forces between the load and the supports.

A cantilever beam is one which is clamped at one end, and loaded at the other. (Figure (ii) 8). There is a neutral layer as before, and again the beam is in tension on one side of the neutral layer, and in compression on the other, and obviously shear stresses will be set up as well.

A clamped or encastre beam is one which is clamped, rather than just supported at each end. (Figure (iii) 8). Here the bending is more complex. There is still a neutral layer,
Figure 8. Beams-Bending.

Figure 9. Work done in Stretching a Bar.
but the stresses on each side of it change in sign from section to section of the beam. Again, shear stresses are set up as well.

2.1.16. STRAIN ENERGY : RESILIENCE. Resilience can be defined as:

(1) The amount of energy per unit volume released upon unloading.

(2) The capacity of a metal, by virtue of high yield strength and low elastic - modulus, to exhibit considerable elastic recovery upon release of load.

WORK DONE IN STRETCHING A BAR. (Salmon)\(^{(49)}\) Let \(AB\) (Figure 9) be a bar of length \(l\), attached at its upper end \(A\), and loaded at its lower end \(B\), with a tensile force which gradually increases from zero to some value \(W\). As the load increases the bar will lengthen; and, while the material remains elastic, the stress will be proportional to the strain, therefore the increase in length \(s_1\) will be proportional to the load \(W\). The triangle \(omn\) will represent the relation between \(s_1\) and \(W\), that is to say, the increase in \(l\) for increasing the values of \(W\). Now the work done on the load in stretching the bar is equal to the average force \(W/2\), multiplied by \(s_1\) the distance moved. Hence the work done is \(\frac{1}{2} Ws_1\) which is equal to the area of the triangle \(omn\). This energy is stored up in the bar and is called the strain energy. If the area of the bar be \(a\), and the stress due to the load \(W\) be \(f\), then \(W = fa\). Further the stress
is equal to $E$ times strain, and the strain is $\frac{6l}{1}$. Therefore, 
$$f = E \frac{6l}{1}, \text{ and } 6l = \frac{f1}{E}.$$  
If $U$ be the strain energy, 
$$U = \frac{1}{2} W \cdot 6l = \frac{1}{2} f a \frac{f1}{E} = \frac{f^2}{2E}. \quad \text{al} = \frac{f^2}{2E} \times \text{(volume of the bar)}$$
for $al$ is the volume of the bar, or as it is sometimes called the internal work. If the load $W$ be increased until the stress $f$ reaches the upper limit of elasticity of the material, the strain energy then stored up in bar will be the minimum amount of work which can be done on the bar without permanently deforming it. This amount of work is called the resilience of the bar. The load producing this stress is the proof load $W_p$, and the stress is called the proof stress $f_p$. If $U_p$ be the resilience
$$U_p = \frac{f_p^2}{2E}. \quad \text{(Volume of the Bar)}$$

The resilience is a measure of the capacity of the member to store up work, and therefore of its capability to resist shock, without plastic deformation, for should the bar sustain a blow, the energy imparted to it by the shock must not exceed the resilience, or the bar will be permanently deformed.

Wahl (63) considers the above case to be an ideal spring, since the bar is loaded axially, the stress distribution across the section is uniform and for this reason this case represents the optimum condition from the viewpoint of maximum storage per unit volume of material. He compares the energy storage capacity of various types of springs, and states that if comparison is made
on the basis of energy stored at first yielding (the extreme fibre is stressed to the yield point) it appears that the simple tension bar spring (Figure 9) is far more efficient than other types. On the other hand, if comparison is made on the more logical basis of energy storage for complete yielding over the section, it appears that the ideal spring is not a great deal more efficient than other types. He emphasises the fact that in the choice of spring type by the designer that a great many factors are involved besides energy storage per unit volume.

2.2. BENDING MOMENTS AND SHEARING FORCES. (Salmon)\(^{(50)}\)

Let AB (Figure 10) be a cantilever projecting from a wall, and suppose that a couple \(M\) be applied at A. The effect of this moment will be to bend the beam as shown in that figure. Such a moment is called a bending moment. It is evident that a similar effect will be produced if, instead of the couple, a vertical load \(W\) be applied at A (Figure 11). Consider any section K at a distance \(x\) from W. The equilibrium of the portion AK of the beam (ii, Figure 11) will not be affected if two equal and opposite forces, of the same magnitude as \(W\) be applied to the beam at K. If the upward force \(W\) at K be considered in conjunction with the downward force \(W\) at A, the two forces evidently form a couple of magnitude \(Wx\), and this couple will cause the beam to bend, just as did the couple \(M\) in Figure 10. The moment \(Wx\) of the couple is evidently the bending moment on
Figure 10. Bending Moment of a Cantilever Beam.

Figure 11. Effect of a Load on a Cantilever Beam.
the beam at the section K.

There still remains the third force \( W \), at \( K \), to be taken into account. This will tend to slide the portion \( AK \) of the beam downwards, relatively to the remainder, as shown at (iii), Figure 11. It tends in fact to shear the beam at \( K \), and is the shearing force at that section.

The load \( W \) at \( A \), therefore, has two effects on the beam at a section such as \( K \). It produces a bending moment which curves the beam, and shearing force which tends to shear the beam.

Next, suppose that there be more than one load on the cantilever (Figure 12), say \( W_1 \) at distance \( x_1 \) from \( K \) and \( W_2 \) at a distance \( x_2 \) from \( K \). As before, consider the equilibrium of the portion \( AK \) (ii, Figure 12), and suppose that two equal and opposite forces of magnitude \( (W_1 + W_2) \) act at \( K \). There are, then, two couples acting on the portion \( AK \), of which the moments are \( W_1 x_1 \) and \( W_2 x_2 \), and the total bending moment at \( K \) is \( (W_1 x_1 + W_2 x_2) \), or the sum of the moments due to \( W_1 \) and \( W_2 \) considered separately.

Further, the shearing force at \( K \) is evidently \( (W_1 + W_2) \) or the sum of the loads \( W_1 \) and \( W_2 \).

If \( W_2 \) act in the reverse direction to \( W_1 \) (iii, Figure 12), it is evident that it would produce a moment and a shearing force of the opposite kind to that produced by \( W_1 \). If the kind of bending and shearing produced by \( W_1 \) be considered positive, that produced by \( W_2 \)
Effect of more than one Load on a Cantilever Beam.

Positive and Negative bending and Shearing.
must be considered as negative, Figure 13 represents positive and negative bending and shearing. These signs are, of course, merely conventions.

By extension from the above reasoning, when all the forces are perpendicular to the beam, the bending moment at any section of the beam may be defined as the algebraical sum of the moments about that section of all forces acting on the beam to the right (or, alternatively to the left) of the section; and the shearing force at any section of a beam may be defined as the algebraic sum of all the forces acting on the beam to the right (or, alternatively to the left) of the section.

2.3. STRESSES DUE TO BENDING. (Salmon)\(^{(50)}\)

2.3.1. THE STRESSES ON A CROSS SECTION, UNIPLANAR BENDING.

Suppose \( K_0 J_0 \) (Figure 14) to be small element of length in a beam originally straight. A bending moment \( M \) acts on the element, distorting it in shape to \( K_1 J_1 K_2 J_2 \). It will be assumed that plane sections of the beam remain plane after bending. That is to say, the plane sections \( K_1 K_0 K_2 J_1 J_0 J_2 \), which are perpendicular to the curved axis of the beam, were plane sections of the beam before distortion, and were perpendicular to the axis, which was then straight.

The outer layer of fibres \( K_1 J_1 \) will be extended by the bending moment, whilst the inner layer of fibres \( K_2 J_2 \) will be compressed. One layer of fibres between these two extremes will be neither
Figure 14.
Stress on a Cross-section; Nonplanar Bending.

Figure 15.
Variation in Stress due to Bending.
extended nor compressed, it will be unaltered in length. Let $K_o H_o J_o$ be this layer. $O$, the centre of curvature of the element, will lie on the intersection of the two planes $K_1 K_o K_2$ and $J_1 J_o J_2$. $O H_o = R$ will be the radius of curvature of the layer $K_o H_o J_o$. Let the angle $K_o O J_o$ be $\delta \theta$.

Consider a layer of fibres $K H J$ distant $x$ from the layer $K_o H_o J_o$. The original length of this layer was the same as that of the layer $K_o H_o J_o$, and the latter is unaltered in length by the bending moment. Therefore, the original length of both layers $K_o H_o J_o$ and $K H J$ was $R \cdot \delta \theta$. The strained length of the layer $K H J$ is $(R + v)\delta \theta$. Hence, the alteration in length of this layer is $(R + v)\delta \theta - R \cdot \delta \theta = v \cdot \delta \theta$, and the strain in it is

$$\frac{\text{alteration in length}}{\text{original length}} = \frac{v \cdot \delta \theta}{R \cdot \delta \theta} = \frac{v}{R}$$

If $E$, the modulus of elasticity of the material, be assumed constant, and $f$ be the stress in the layer, then

$$f = E \times \text{strain} = E \cdot \frac{v}{R} ; \text{or } \frac{f}{v} = \frac{E}{R} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (7)$$

Since $\frac{E}{R}$ is constant for the element under consideration, $f$ varies as $v$; that is to say, the stress in any layer of fibres varies directly as the distance of that layer from the layer unaltered in length by the bending moment. The diagram (ii, Figure 15) representing the variation in stress, is a straight line. At the layer $J_o H_o K_o$ (Figure 14), $v = 0$,
and the stress is zero. This layer of fibres is called the neutral surface, and its intersection with the plane of bending is called the neutral line. The line N.A (i, Figure 15), which represents the section of the neutral surface by any right transverse cross-section, is called the neutral axis. For layers of fibres above the neutral surface, \( \nu \) is positive; and if, as in Figure 14, the bending moment is positive, the stress is tensile (positive). For layers of fibres below the neutral surface, \( \nu \) is negative; and the stress is compressive (negative). This is clearly shown by the double triangle of (ii) Figure 15, which represents the variation of stress over the cross-section.

The maximum tensile stress \( f_1 \) will occur in the extreme layer of fibres, \( \nu = \nu_1 \), on the extended side of the beam.

From equation (7)

\[
f_1 = \frac{E \nu_1}{R} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (8)
\]

Similarly, the maximum compressive stress \( f_2 \) will occur in the extreme layer of fibres in compression \( \nu = -\nu_2 \), its magnitude is

\[
f_2 = \frac{-E \nu_2}{R} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (9)
\]

the negative sign denoting compression.

2.3.2. POSITION OF NEUTRAL AXIS. Let \( b \) (i, Figure 15) be the breadth of the layer of fibres distant \( \nu \) from the neutral axis. If \( \delta_v \) be the thickness of the layer, its area is \( b \cdot \delta_v \).

The force on this layer is \( fb \cdot \delta_v \), where \( f \) is the stress therein.
Hence the total force $F_1$ (iii, Figure 15) on that part of the
cross-section above the neutral axis is

$$ F_1 = \int_0^{V_1} fb. \ dv. = \frac{E}{R} \int_0^{V_1} bv. \ dv. \quad \ldots \quad (10) $$

Similarly, the total force on that part of the cross-section
which is below the neutral axis is

$$ F_2 = \int_0^{-V_2} fb. \ dv. = \frac{E}{R} \int_0^{-V_2} bv. \ dv. \quad \ldots \quad (11) $$

The total longitudinal force on the cross-section of the beam
will be $F_1 + F_2$, but since these forces are produced by a bending
moment only, and no longitudinal force exists, it follows that

$$ F_1 + F_2 = 0 \quad \text{or} \quad F_1 = -F_2 \quad \ldots \quad (12) $$

and that,

$$ F_1 + F_2 = \frac{E}{R} \int_0^{V_1} bv. \ dv. + \frac{E}{R} \int_0^{-V_2} bv. \ dv. $$

$$ = \frac{E}{R} \int_{-V_2}^{V_1} bv. \ dv. = 0 $$

From which

$$ \int_{-V_2}^{V_1} bv. \ dv. = 0 \quad \ldots \quad (13) $$

But

$$ \int_{-V_2}^{V_1} bv. \ dv. = a\bar{v}, \text{where} \ a \text{is the area of the} $$

$$ \text{cross-section, and} \ \bar{v} \text{is the distance of its centre of area} $$

$$ \text{from the neutral axis. Hence, from equation (13) } a\bar{v} = 0, $$

$$ \bar{v} = 0. \text{ That is to say, the neutral axis passes through the} $$
centre of area of the cross-section. Since the bending is uniplanar, the neutral axis will be perpendicular to the plane of bending.

2.3.3. THE MOMENT OF RESISTANCE. The bending moment upon the element will be resisted by an equal and opposite moment of the internal stresses set up in the beam. This moment of the internal stresses is called the moment of resistance. It is evidently the moment of the resultant tensile and compressive forces $F_1$ and $F_2$ (ii, Figure 15) which act on the cross-section. These have been shown to be equal (Equation 12). Therefore, they form a couple, and moments may be taken about any point. Take moments about the neutral axis. The force on a layer of fibres distant $v$ from the neutral axis has been shown to be $fb. \delta v. = \frac{E}{R} bv. \delta v$. The moment of this force about the neutral axis is $fbv. \delta v. = \frac{E}{R} bv^2. \delta v$. Hence the total moment of all such forces on the cross-section, which is the moment of resistance, is

$$\frac{E}{R} \int_{-v_2}^{v_1} bv^2. dv. \text{ But } \int_{-v_2}^{v_1} bv^2. dv = I,$$

where $I$ is the moment of inertia of the cross-section about an axis through its own centre of area perpendicular to the plane of bending, i.e. about the neutral axis. Hence the moment of resistance, which is equal to the bending moment $M$, is $\frac{EI}{R} = M$; and it follows from Equation (7) that
\[ \frac{M}{I} = \frac{E}{R} = \frac{f}{v} \]  

............... (14)

\[ f = \frac{Mv}{I} \]  

............... (15)

At the extreme fibres in tension, \( f = f_1 \), and \( v = v_1 \).

Therefore,

\[ f_1 = \frac{Mv_1}{I} \]  

............... (16)

Similarly, at the extreme fibres in compression

\[ f = f_2 \quad \text{and} \quad v = -v_2 \]

Therefore, \( f_2 = -\frac{Mv_2}{I} \)  

............... (17)

Now \( \frac{I}{v_1} \) and \( \frac{I}{v_2} \) are called the moduli of resistance of section moduli of the cross-section and are represented by the letter \( Z_1 \) and \( Z_2 \) respectively.

Hence, \( M = f_1 Z_1 = f_2 Z_2 \)  

............... (18)

From these equations the stresses in a beam due to bending can be determined.

The foregoing is usually referred to as the Theory of Simple Bending. A number of assumptions have been made or implied and the theory is only approximate. Nevertheless as proved by practice and experiment, it is sufficiently accurate for ordinary engineering problems and may with confidence be applied to them. A more exact theory, taking into account the shear stresses, has been given by Saint-Venant, and will be found in treatises on the Theory of Elasticity.(61)
2.3.4. THE MOMENT OF INERTIA. The moment of inertia of the cross-section about a principle axis through the centre of area is given by the integral, \( I = \int_{v_2}^{v_1} b v^2 \, dv \). (see 2.3.3.) For simple cross-sections this integral can be evaluated directly (Salmon)\(^{(50)}\). In more complicated cases direct integration may not be convenient or even possible.

2.3.5. CALCULATION OF BENDING STRESSES IN A BEAM. Given a beam loaded in any specified manner, to find the maximum bending stresses on any cross-section. From the given load system, find \( M \) the bending moment at the cross section. Calculate the values of the section moduli \( Z_1 \) and \( Z_2 \) from the dimensions of the cross-section. Then from Equation 18, the stresses at the extreme fibres of the cross-section are \( f_1 = \frac{M}{Z_1} \); \( f_2 = \frac{M}{Z_2} \); or alternatively from Equations 16 and 17

\[
\begin{align*}
  f_1 &= \frac{M v_1}{I} \quad \text{and} \quad F_2 = \frac{M v_2}{I}
\end{align*}
\]

One of these will be the maximum bending stress on the cross-section.

2.4. DEFLECTION OF BEAMS (Salmon)\(^{(50)}\)

CURVATURE. Let \( JKH \) (Figure 16) be part of the deflection curve of a beam, and \( K \) and \( H \) any two neighbouring points on that curve. Let the co-ordinates of \( K \) be \( x \) and \( y \), and those of \( H \) be \( (x + 6x) \), \( (y + 6y) \). The ordinate \( y \) is the deflection of the beam from the straight line \( Ox \) at a point distant \( x \) from the origin \( O \). Draw \( KT_1 \), \( HT_2 \) tangents to the curve at \( K \) and \( H \) respectively, and produce
Figure 16. Deflection of Beams - Curvature.

Figure 17. Bending Moment and Shearing Force Diagrams of a Cantilever Spring.
$T_1 K$ to meet $T_2 H$ in $Q$. Let the angle $K T_1 x$ be $\theta$
and $H T_2 x$ be $(\theta + \delta \theta)$. Then the angle $H T_2 x$ is equal to the
angle $K T_1 x$ plus the angle $T_1 Q T_2$. Hence the angle $T_1 Q T_2 = \delta \theta$
Draw $K C$ and $H C$ perpendicular to $K T_1$ and $H T_2$ respectively;
the angle $K C H$ is equal to $\delta \theta$.
Let $K H = \delta s$. Then if $C K = R$, $\delta \theta = \frac{K H}{C K} = \frac{\delta s}{R}$
and $\frac{1}{R} = \frac{\delta \theta}{\delta s}$. In the limit when $\delta \theta$ is very small, $K$ and $H$
become consecutive points, $R$ becomes the radius of curvature
at $K$, and

$$\frac{1}{R} = \frac{d \theta}{d s} \quad \cdots \quad (19)$$

Now $\tan \theta = \frac{dy}{dx}$, differentiate with respect to $s$,

$$\sec^2 \theta \frac{d \theta}{d s} = \frac{d^2 y}{dx^2} \cdot \frac{dx}{d s}$$

In the limit, when $\delta x$ is very small, $\frac{\delta x}{\delta s}$ becomes

$$\frac{dx}{ds} = \cos \theta \quad (ii, \text{Figure 16})$$

Hence $\frac{d \theta}{d s} = \frac{d^2 y}{dx^2} \cdot \frac{1}{\sec^2 \theta} = \frac{d^2 y}{dx^2} \cdot \frac{1}{(1 + \tan^2 \theta)^{3/2}}$ or,

from Equation 19

$$\frac{d \theta}{d s} = \frac{1}{R} = \frac{\frac{d^2 y}{dx^2}}{\left\{1 + \left(\frac{dy}{dx}\right)^2\right\}^{3/2}} \quad \cdots \quad (20)$$

$1/R$ is usually called the curvature of the beam at the point $K$.

Equation 20 is the ordinary expression for the curvature in terms
of the co-ordinates of the curve. In a beam, the curvature is
always very small, and $\theta$ is a very small angle. Therefore $\tan \theta$

$$\frac{dy}{dx} \quad \text{is very small, and} \quad \left(\frac{dy}{dx}\right)^2 \quad \text{can be neglected in comparison}$$
with unity. Equation 20 then reduces to

\[ \frac{1}{R} = \frac{d^2y}{dx^2} = \frac{M}{EI} = \frac{f}{Ev} \quad \cdots \quad (21) \]

since, from Equation 14, \( \frac{M}{I} = \frac{E}{R} = \frac{f}{v} \)

The deflection of the beam can be found by solving the differential equation (21).
CHAPTER 3

STRUCTURAL INTERPRETATION OF PHYSICAL PROPERTIES OF MATERIALS.

In general, a structure may be defined as the definite arrangement of material in a form adapted to the accomplishment of a purpose by the transmission or absorption of force (Brumfield)\(^8\). The form of the structure as well as its material is important in carrying out this purpose and both these factors must be considered in determining the ability of a structure to accomplish its purpose.

3.1. STRENGTH OF STRUCTURE - ELASTIC AND INELASTIC

Structural strength may be defined as the maximum load, of a given character, which the structure can carry (Brumfield)\(^8\). Since the structure may be required to carry more than one type of load, it is obvious that it may have more than one strength. It is usually true, however, that one of the types is a critical or controlling one, and strength will be interpreted in terms of this load type. There are two distinct types of strength under steady load. These are elastic strength and inelastic strength. The elastic strength of the structure would be the biggest load of controlling type which the structure can support without permanent distortion. The inelastic strength of the structure would be the load of critical type to rupture the structure. In bending which is the loading type ordinarily used in orthodontic structures, the strength would be limited to that load which would induce the proportional limit stress at
any point within the structure. This strength depends on the material and on the form of the structure. However, in comparing two structures identical in form but of different materials, the influence of the form of the structure would cancel, for purposes of comparison, and the elastic strength would then vary directly as the proportional limits of the materials. In a similar manner, inelastic strengths on a comparative basis, for identical structures of different materials, vary directly as the ultimate strengths of the materials of which the two structures are made. Though structural form may have an influence on strength, the physical properties of the materials become useful from a comparative standpoint, when structural forms have considerable similarity.

While the proportional limit is a measure of the upper limit of elastic strength, Brumfield, and Smith and Storey, both caution against applying the full elastic load to any structure. This is particularly true of orthodontic structures because of uncertainties surrounding the structure in use in the mouth. If a load greater than the elastic strength of the structure is inadvertently applied the structure would distort permanently and fail to carry out its intended function. It is a common practice that the working load of a spring be somewhat below the full elastic strength (Wahl).
3.2. **FLEXIBILITY OF STRUCTURE**

The flexibility of structure is the amount of distortion, of any given character, which the structure undergoes when a load within its elastic strength is applied to it (Brumfield). The term is usually reserved for distortion due to bending. Flexibility depends on the physical properties of the materials of which the structure is fashioned and on the general form and detailed dimensions. The two properties of materials which are pertinent to the flexibility of all structures are proportional limit and modulus of elasticity. The higher the proportional limit the greater the flexibility under given conditions. Inversely, the higher the modulus of elasticity the less the flexibility, other conditions being constant. The flexibilities of most orthodontic structures are in the main, required under conditions which bring bending forces to bear on the structural parts. The general law of flexibility in bending is

\[ y = K \frac{f_p L^2}{E v} \]  \hspace{1cm} (22)

where \( y \) is the flexibility of the structure

\( f_p \) is the proportional limit of the material

\( L \) the length of the structure under bending

\( v \) the depth of the structure (for symmetrical sections) in the plane in which bending occurs. The values of \( v \) may be constant or variable depending on conditions.
K is constant for any given structure. It reflects the type of loading and type and manner of supports at the ends of the beams. In the case of a cantilever beam, with a single concentrated load at the end K is 1/3. For more complicated structures, the value of K may be difficult to determine. Nevertheless, the equation is useful for comparative purposes. If it is desired to make a comparison of the possible flexibilities of two structures from different materials, but in identical structural forms, the value of K, whatever it may be, will cancel and the physical properties of the materials become the determining factors in making the comparisons. Such comparisons are of value for semi-design purposes. (Brumfield (9) gives tables enabling comparison of various types of materials suitable for a range of orthodontic springs.)

3.3. COMPARATIVE DESIGN OF STRUCTURES FROM WROUGHT WIRE.

Orthodontic structures are primarily subjected to bending loads and their detailed dimensions are determined by bending stresses. For structures loaded in bending the following general law applies (Brumfield) (10)

\[ W = K \frac{P}{V} \frac{I}{V} \quad \ldots \ldots \quad (23) \]

or, for a circular section,

\[ W = K_1 \frac{P}{V} \frac{d^3}{V} \quad \ldots \ldots \quad (24) \]

In the above equations 23 and 24, W represents the load of any given character which the structure may safely carry in bending and is therefore, its strength; \( P \) is the proportional limit of
the material of which the structure is built; $\frac{I}{V}$ is the section modulus of the structure perpendicular to the plane in which maximum bending occurs; and $K$ is a constant which depends on the kind of loading, the general character of the structure and the method of supporting it. In the second equation $K$ is a similar constant but not the same one; $d$ is the depth of the structure, \( \text{(for a circular section } \frac{I}{V} \text{ is equal to } \frac{d^3}{32} \text{ for bending).} \)

Both these equations may be used for comparing two structures whose forms are sufficiently alike that their $K$-values are the same. If it is assumed that a satisfactory orthodontic appliance has been worked out in terms of a given material, the necessary dimensions of a similar structure from a different material may be determined by comparison. Brumfield believes that flexibilities of structures may be compared quite successfully so long as their general form remains the same.

3.3.1. BENDING MOMENT OF A CANTILEVER SPRING. (Salmon)\(^{(50)}\)

As an example consider a cantilever, length $L$, loaded with concentrated load $W$ at its free end. The shearing force and bending moment diagrams for this case are given in (ii) and (iii) Figure 17. At any section $K$, distant $x$ from $A$, the shearing force is equal to $W$, hence the shearing force diagram is a rectangle $a\ b\ c\ d$. The bending moment $M_k$, at $K$, is $Wx$. Hence the bending-moment diagram is a triangle $a'\ b'\ c'$, the ordinate at $a'$, where $x = 0$, is zero, and at $b'$, where
x = L, is w.l. This is the maximum bending moment on the cantilever. The vertical reaction at the wall is equal to W, and the wall must also be capable of resisting the bending moment W. L.

3.3.2. DEFLECTION OF CANTILEVER SPRING (Salmon)\(^{(50)}\). In the following case it will be assumed that both E and I are constant. Consider a uniform cantilever spring, span L, loaded with concentrated load W at the free end (Figure 18). Let A be the origin and, consider any section K distant x from A. Let \( y \) be the deflection there. The bending moment at K is \( M = W (L - x) \).

From Equation (21)

\[
\frac{d^2 y}{dx^2} = \frac{M}{EI} - \frac{W}{EI} (L-x)
\]

Integrating this, E, I being constant,

\[
\frac{dy}{dx} = \frac{W}{EI} \left\{ Lx - \frac{x^2}{2} \right\} + C_1 \quad \ldots \ldots \quad (25)
\]

At the origin, where \( x = 0 \), the beam is horizontal, hence,

\[
\frac{dy}{dx} = 0, \text{ and } C_1 = 0. \quad \text{From Equation (25) the slope of the beam everywhere can be obtained.}
\]

Integrate again,

\[
y = \frac{W}{EI} \left\{ \frac{Lx^2}{2} - \frac{x^3}{6} \right\} + C_2 \]

At the origin, where \( x = 0 \), the deflection \( y = 0 \) and hence \( C_2 = 0 \).

Therefore, \( y = \frac{W}{EI} \left( \frac{Lx^2}{2} - \frac{x^3}{6} \right) \quad \ldots \ldots \ldots \ldots \quad (26)\)

This equation gives the deflection at any section K. The maximum deflection occurs at B where \( x = L \).
Figure 18. Deflection of a Cantilever Spring.

Figure 19. Linear Load-Deflection Curve of a Typical Spring.
\[ \text{Max } y = \frac{W L^3}{3EI} \]  
\[ \text{(27)} \]

The maximum bending moment which measures the strength is given as;

\[ M = WL \]  
\[ \text{(28)} \]

The maximum stress in the beam is equal to

\[ f = \frac{MV}{I} \]  
\[ \text{(29)} \]

where \( M \) is the bending moment and \( \frac{I}{v} \) is the section modulus of the beam, and the distance from the neutral axis to the most remote edge of the section is \( v \). In the case of a circle or other sections whose gravity axis lie at the centre, \( v \) is half the depth. The equation for flexibility of a cantilever beam may then be re-written as follows

\[ \text{Max.} y = \frac{WL}{3EI} \frac{L^2}{v} = \frac{MV}{I} \frac{L^2}{3Ev} = \frac{FL^2}{3EI} = \frac{KFL^2}{Ev} \]  
\[ \text{(30)} \]

The flexibility of this beam is equal to the product of a constant, the greatest unit stress in the beam, the square of the span length, divided by the product of the modulus of elasticity of the material and half the depth. Except for the constant \( K \), which depends on the characters of the loads and supports, the flexibilities in bending of all structures have the same mathematical form. Flexibility varies directly as the greatest stress in the structure, which would have a limiting value equal to the proportional limit, and the square of the effective length in bending. It varies inversely as the modulus of elasticity of the material times the depth of the structure.
Consider the flexibilities and strengths of two structures 1 and 2, of the same general form, same lengths of structure in bending but of different materials and of different cross section perpendicular to the plane of bending.

From Equation (22)

\[
\text{Maximum } y_1 = \frac{K_1 f_{p1}}{E_1 v_1} \quad \text{and maximum } y_2 = \frac{K_2 f_{p2}}{E_2 v_2}
\]

If the loads are identical and both structures are of same general form \( K_1 = K_2 \), and if both are to have the same flexibility,

then,

\[
\frac{f_{p1}}{E_1 v_1} = \frac{f_{p2}}{E_2 v_2}
\]

............... (31)

for a circular section \( v = \frac{d}{2} \) (where \( d \) is the diameter of the circular section)

then,

\[
\frac{f_{p1}}{E_1 d_1} = \frac{f_{p2}}{E_2 d_2}
\]

............... (32)

If the two structures are to have the same strengths, then from Equation (23)

\[
W_1 = K f_{p1} \frac{I_1}{v_1} \quad \text{and } W_2 = K f_{p2} \frac{I_2}{v_2}
\]

Now, if \( W_1 = W_2 \) (i.e. same strengths)

then

\[
\frac{f_{p1}}{v_1} = \frac{f_{p2}}{v_2}
\]

............... (33)

for a circular section \( \frac{I}{v} = \frac{d^3}{32} \) (Salmon)(50)

then

\[
\frac{f_{p1} d_1^3}{v} = \frac{f_{p2} d_2^3}{v}
\]

............... (34)
CHAPTER 4

GENERAL CONSIDERATIONS IN ORTHODONTIC SPRING DESIGN.

The first criterion for wire usage is the capability of delivering a specific amount of force. Several studies have been made of the amount of force required for specific tooth movements, Storey and Smith (57) have reported the optimum range of force for retraction of the lower cuspid is between 150-250 grams. Burstone and Groves (13) retracted anterior teeth by simple tipping and stated optimum rates of tooth movement were observed when 50-75 grams of force were applied. Reitan (42) has stated that the maximum force needed during any stage of a continuous bodily movement of canines is 250 grams. Reitan (43) also observed tooth movement by tipping when a force of 50 grams was applied.

Wahl (65) defines a mechanical spring as an elastic body whose primary function is to deflect or distort under load and which recovers its original shape when released after being distorted. Provided that the material is not stressed beyond the proportional limit, the usual type of spring will have a straight-line load deflection diagram as shown in Figure 19, provided geometry does not change during deformation. This means that the deflection is proportional to the load, i.e., if the load is doubled the deflection will be doubled. The relation will hold true even if the acting load is a torque or moment, provided linear deflection is replaced by angular deflection.
The forces used in orthodontic appliances have their origin primarily in elastically deformed wires. Since orthodontists are concerned with the "elastic" or "spring" properties of wire, it is desirable to refer to such mechanisms simply as orthodontic springs. Orthodontic springs may take advantage of either the bending or torsional properties of a wire. A finger spring and a vertical loop are examples of force derived from bending a wire. In a coiled extension or compression spring or a third order bend (torque) in an edgewise archwire, the force is obtained from the twisting or torsional properties of the wire. In order to design and utilize springs for orthodontic appliances, three spring characteristics must be considered (Burstone)\(^{(14)}\). They are:

1. The relationship between load and deflection.
2. The load at which permanent deformation occurs.
3. The range of activation within the elastic limit.

The deflection at which permanent deformation occurs is described by Hooke's law which can be interpreted as stating that within the proportional limit of any material deflection is proportional to load. Hence, throughout the range of action of a spring, the quotient of applied force divided by deflection is constant. This constant is termed the spring constant, spring-rate or the load-deflection rate, and is usually given as grams per millimetre or gram millimetres per radian. Haack\(^{(27)}\) designated the ratio of force to deformation...
the "stiffness". It represents the load necessary to produce a unit deflection. Load-deflection rates vary considerably in commonly-used orthodontic appliances and in some applications the load-deflection rate may vary in a given spring particularly if large deflections are employed. (Burstone (14), Wahl (65)). This is not a contradiction of Hooke's Law, but reflects the changes in spring configuration that occur during loading. This probably involves combined bending and torsion instead of simple bending and torsion. Since these springs lack a linear relationship of load and deflection, an average rate may be used to describe the force gradient. For greater accuracy, however, a table or graph showing the force per unit of activation is preferable to predicting the force on the basis of an average spring constant. If successive loads are placed on a spring, a point is reached at which permanent deformation will occur. The greatest load that can be applied safely to a wire without permanent deformation is the "proof load" and it is determined usually both by theoretical calculations and experimental data. The largest force placed on a member during a given action is the final load. In order to minimize accidental permanent deformation in springs, it is desirable to apply a final load that is considerably less than the proof load. Closely related to the proof load is the range of action per static loading. The range of action is the greatest distance through
which a flexible member can be deflected without permanent deformation. Springs that have high proof loads and low-load deflection rates have high ranges of action. The desirability of continuous force in orthodontics may be questioned if high load-deflection rates are employed. A high spring-rate acting continuously between appointments will demonstrate a marked lack of uniformity in force magnitude. For this reason, appliances of this type must be activated so that the final load is great enough to ensure an average force level which is adequate for tooth movement. Physiologically, the final load is apt to be too large and hence, undesirable changes in the periodontium may follow.

The ideal orthodontic spring would have the ability to release a constant force throughout the entire range of its activation. This is not to imply that force levels should remain constant during a given range of tooth movement, but rather that sudden changes in force magnitude should be eliminated. Since Hooke's Law indicates that no spring is constant in its action, the request for a constant force spring resolves itself into the utilization of springs with low load-deflection rates. In these terms a constant-force spring is one that approaches a zero rate. With a low spring rate it is necessary, however, to assume a sufficiently high proof load to prevent permanent deformation before reaching the final load. It can be seen that the design of relatively constant-force springs requires the development of
flexible members that have both low rates and high maximum working loads. Mechanisms of this type are characterised by long ranges of activation and the ability to absorb considerable energy.
CHAPTER 5

FACTORS INFLUENCING ORTHODONTIC SPRING DESIGN

5.1. MECHANICAL PROPERTIES OF WIRE

The mechanical properties of the wire used in an orthodontic spring may alter both the rate and proof load of the spring.

From Equation 21

\[
\frac{d^2y}{dx^2} = \frac{M}{EI}
\]

and \( M \propto W_L \).

then \( \frac{W}{y} \propto \frac{EI}{L} \)

For any given spring \( \frac{1}{L} \) is a constant therefore spring rate \( \frac{W}{y} \) is directly proportional to the modulus of elasticity. The modulus of elasticity represents a stress-strain ratio in compression or tension which expresses a measure of stiffness of a material. It is basically a constant for most wires but with some wires it can be altered quite significantly by heat treatment or work hardening. (i.e. cobalt chromium wire after heat treatment, work hardening, Mutchler\(^{[39]}\).)

If spring configuration and dimension remain unchanged, rate may be altered only by using various alloys with differing moduli of elasticity. (See Table 1.) If we compared similar springs of the two materials listed in Table 1, the steel spring would deliver more force for each millimeter of action than the gold spring, but the gold spring would have a range of action approximately twice that of the steel spring.
### TABLE 1

**COMPARISON OF MECHANICAL PROPERTIES OF TYPICAL GOLD AND STAINLESS STEEL WIRE** *(ANDERSON)*

<table>
<thead>
<tr>
<th></th>
<th>Gold Alloy Wire 10-20% Pt. and Pd.</th>
<th>18-8 Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annealed</td>
<td>Heat Hardened</td>
</tr>
<tr>
<td>Proportional Limit</td>
<td>50</td>
<td>74</td>
</tr>
<tr>
<td>(Kg/mm$^2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>70</td>
<td>105</td>
</tr>
<tr>
<td>(Kg/mm$^2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>11,000</td>
<td>11,000</td>
</tr>
<tr>
<td>(Kg/mm$^2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elongation</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>(per cent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B.H.N.</td>
<td>180</td>
<td>260</td>
</tr>
</tbody>
</table>
The mechanical property of an alloy that determines proof load is the proportional limit. Provided that the maximum stress in the cross section does not exceed the proportional limit of the material the beam or spring will behave elastically. The higher the proportional limit the greater is the proof load. Proportional limit can be affected markedly by composition, grain size, cold working and heat treatment. (Skinner)\(^{53}\), (Metals Handbook)\(^{(36)}\). Cold working increases the yield strength of wire (Metals Handbook)\(^{(36)}\) and since smaller diameter wires usually are subjected to greater cold working they will tend to have a higher proportional limit than larger diameter wires. (Wilkinson)\(^{(68)}\).

Heat treatment further increases the proportional limit of some wires. (Metals Handbook)\(^{(36)}\). Burstone \(^{(28)}\) considered that not all residual stresses are undesirable, for in many instances if these stresses are properly orientated they may increase the proportional limit. He believed that confusion sometimes exists in relating resistance to permanent deformation and the rate of a spring. On the basis of "feel", a clinician may believe that a spring made of soft steel wire has a lower spring rate than an identical spring fabricated of hard steel. It should be remembered that modulus of elasticity is approximately constant for a given steel alloy and, therefore, that the rates of identical soft and hard steel wire springs are nearly the
same. The difference in "feel" can be explained by the higher proportional limit of the hard wire which requires a greater total force to produce permanent deformation.

5.2. CROSS SECTIONAL GEOMETRY OF ORTHODONTIC WIRES.

The change in rate which occurs as a result of altering the cross section of a spring wire is not simply proportional to the change in the wire dimension or to the cross sectional area. The resistance of a wire to bending and hence, its rate, is determined by the distribution of the material around the neutral axis. (See section on Deflection of Beams, 2.4.)

It can be demonstrated that a relatively small increase or decrease in the cross section of a wire may result in a marked increase or decrease in the load deflection rate of an orthodontic spring. Specifically for round wire the spring rate increases as the fourth power of the diameter of the cross section. (Fig. 20). For instance, if a 0.020 in. wire and a 0.040 in. wire are deflected the same distance, the 0.040 in. wire exerts sixteen times as much force as the 0.020 in. wire although the diameter of the 0.040 in. wire is only twice as great. For square or rectangular wires (Figure 20) the spring rate is only directly proportional to the width, b, of the cross section but increases as the cube of the depth h. Thus a change in depth has a much more pronounced effect on the amount of force required for a given deflection than does a change in the width of the cross
Figure 20.

CHARACTERISTICS—BEAM SECTIONS

<table>
<thead>
<tr>
<th>Moment of Inertia</th>
<th>Section Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I = \frac{bd^3}{12}$</td>
<td>$I = \frac{bd^2}{6}$</td>
</tr>
<tr>
<td>$I = \frac{\pi d^4}{64}$ – Bending</td>
<td>$I = \frac{\pi d^3}{32}$ – Bending</td>
</tr>
<tr>
<td>$I_T = \frac{\pi d^4}{32}$ – Torsion</td>
<td>$I = \frac{\pi d^3}{16}$ – Torsion</td>
</tr>
</tbody>
</table>
section. For instance, the result of decreasing the depth by half is to reduce the spring rate by a factor of eight, but, if the width is decreased by the same amount the rate is reduced by a factor of two.

A low rate spring could be designed simply by reducing the dimensions of the wire cross section. However, this approach is limited by the fact that the proof load changes as the third power of the diameter in round wires, and as the breadth times the second power of the depth in rectangular wire. If the dimensions of the cross section are reduced too radically, the resultant decrease in maximum load may result in permanent deformations of a spring during its normal use. For example an 0.040 in. wire spring can withstand elastically approximately eight times as much loading as an 0.020 in. wire spring of the same design and alloy. Similarly an 0.010 in. x 0.020 in. rectangular wire can withstand elastically, only one eighth of the load supported by an 0.020 x 0.020 wire.

The optimal cross-sectional shape is determined by the loading conditions to which a spring is subjected. If a wire is to be bent in many directions during normal use, a round cross-section is desirable. The most advantageous cross section for unidirectional bending is flat wire. If two similar flexible members, except for cross-section, can support identical maximum loads, it is found that their rates vary as their
diameters (round wires) or breadths and depths (rectangular wires). The rates vary as the distance from the neutral axis to the most remote fibre in the plane of bending. As an example, a cantilever spring fabricated from 0.023 in. diameter round wire and a similar spring of an 0.006 x 0.20 rectangular wire of the same material may be compared since the maximum loads for both springs are (almost) identical. By calculation the 0.023 in. round wire has a rate three times as great as the flat wire spring.

5.3. WIRE CONFIGURATION OF ORTHODONTIC SPRINGS
Burstone (14), Jarabak (31), Smith and Storey (58), show that modification of the linear configuration can offer potential in altering the rate and proof load of a spring. They give examples of the effect of wire length, incorporation of helixes and spring design on the rate and proof load of a spring. Since the possibilities of design are numerous, consider a cantilever and assume that the load W is always applied at a right angle to the long axis of the wire in the plane of bending, throughout the range of action. A change in length of a cantilever produces a more dramatic effect on rate than on proof load. From Equation (22)

\[
\text{for a cantilever maximum deflection } = \frac{WL^3}{3E d^4}
\]

specifically the rate varies inversely as the cube of the length

From Equation (23)

\[
\text{for a cantilever maximum load } = \frac{Fp\pi d^3}{32L}
\]
and the proof load varies inversely as the first power of the length. The effect of wire length can be illustrated by comparing a 10 mm. and a 20 mm. cantilever spring fabricated from the same wire. In respect of rate, the 10 mm. spring has a gradient eight times as great as the 20 mm. one. Yet the allowable load is only twice as high for the 10 mm. cantilever.

Modification of a cantilever along its length by the placement of coils or loops reduces spring rate without affecting proof load.

Although bends may be placed anywhere along the length of wire, the optimum position for the incorporation of additional wire is where the bending moment is maximal. Since the bending moment is directly related to the degree of bending at any cross section of wire, the greatest elastic deformation will occur where the bending moment is greatest. It is at this point that additional wire most effectively reduces the load deflection rate. The maximal bending moment of a cantilever loaded with a single transverse force is at its fixed end which is most remote from the point of force application. The incorporation of a helix in the area of maximum bending decreases the spring rate without significantly altering the ability of the spring to withstand permanent deformation.

Burstone\(^{(14)}\) gives the spring rate in a cantilever spring modified with a helix as being determined by the diameter of the helix, number of turns in the helix and the length of the
cantilever.

\[ \frac{W}{D} = \frac{E I}{2 \pi n \left( L^2 + \frac{r^2}{2} \right) \times 4D r^2 + \frac{L^3}{3}} \]

where

\( E \) = modulus of elasticity

\( I \) = moment of inertia

\( n \) = number of turns in helix

\( L \) = length of arm

\( r \) = radius of helix

\( \frac{W}{D} \) = load deflection rate

For example, if a 10 mm. cantilever is compared to a cantilever (of the same wire) with one turn in a 3 mm. helix, it is found that the rate of the modified cantilever is reduced to about one half (forty six per cent). On the other hand, if two turns are placed in the helix the rate diminished by fifty eight per cent.

The elimination of sharp bends enhances the elastic properties of a spring. If a bend is acute, stress concentration will occur at this point and permanent deformation is more likely to result when the wire is loaded. This danger is greatest where the bending moment is maximum and it is here that acute bends should be particularly avoided. Burstone\(^{(14)}\) concludes that:

1. Load/deflection rates can be lowered by reducing the cross-sectional area.

2. The greatest potential in altering spring properties is found in the linear configuration. The placement of
additional wire where the bending moment is maximal lowers
the rate without changing the maximum load that may be
sustained without permanent deformation.

3. Although the mechanical properties of a wire partly
determine its action, the primary factor in the delivery of
continuous force is the design of the spring.
CHAPTER 6

MATERIALS

6.1. STAINLESS STEEL

Rust resisting iron-chromium alloys were discovered by Brearley in 1913, and developed by Strauss and Maurer in Germany in 1913 (Monypenny)\(^{(38)}\), but probably were not generally available until around 1919 and were introduced in the orthodontic field in the United States around 1929 or 1930 (Gaston)\(^{(25)}\). De Coster\(^{(18)}\) (1932) reported that stainless steel had been used for orthodontic purposes in Belgium since 1924.

The material in which we are primarily interested in orthodontics is A.I.S.I. type 302, which contains (in addition to the iron content) the following chemicals: carbon 0.15% maximum; manganese 2% maximum; silicon 1% maximum; chromium 17-19%; nickel 8-10%. Another alloy which is very similar to this, and has almost identical physical properties is type 304, the main difference between the two being that 304 contains only 0.08% carbon maximum, and from 18-20% chromium and 8-12% nickel. These alloys are austenitic, very high in corrosion resistance, non-magnetic when annealed but slightly magnetic when cold worked (Gaston)\(^{(25)}\).

American workers found this material difficult to solder, initially, because the fluxes used could not dissolve the outer surface oxides. When this problem was overcome, it was
found that joints of excellent appearance discoloured and broke apart after two to ten weeks in the mouth. (Gaston)\(^{(25)}\), (Brusse and Carmen)\(^{(12)}\), (Bell)\(^{(5)}\). Even in 1951 Gaston\(^{(25)}\) wrote of the technique of spot welding before soldering to overcome the difficulty of wires sliding out of the enveloping solder, although this difficulty is not present today.

Spot welding was probably introduced about 1930 in Europe (De Coster)\(^{(18)}\) and about 1933 in the United States (Walsh)\(^{(66)}\). Simon\(^{(53)}\) in 1922 described the use of tin solders for stainless steel in orthodontics which suggests that Europeans were in difficulty with soldering these alloys. By 1933 chrome alloy wires were being used successfully by a numbers of workers in the United States (Gaston)\(^{(25)}\). However as late as 1937 widely differing opinions of the relative merits of soldering and spot welding were expressed, even though Vosmik and Taylor\(^{(62)}\) in 1933 had demonstrated the benefits of silver solders (without explicitly examining the tendency for joints to break).

The suitability of stainless steel wires for orthodontic appliances is primarily due to the following properties:

1. Great strength.
2. High modulus of elasticity.
3. Resistance to corrosion in the mouth.
4. Low cost as compared to precious metal alloys.

6.1.1. GENERAL CONSIDERATION OF HARD DRAWN STAINLESS STEEL ARCH WIRE. (Wilkinson)\(^{(68)}\). In the annealed state austenitic steel
consists of roughly equiaxed grains. High tensile strength and high proportional limit can be induced in these steels by plastic deformation below the recrystallisation temperature. The finer the grain size before cold working, the greater will be the improvement in the mechanical properties. Grain size can be reduced by alternate plastic deformation and recrystallisation. In manufacturing practice, a wire is drawn down to size in stages. The drawing process distorts the grains into tiny fibrous shapes, elongated along the length of the wire. When softening is required the wire is heated to a temperature which will cause recrystallisation of the metal. The process of recrystallisation is governed mainly by two factors - temperature and time. The higher the temperature the faster the rate of recrystallisation. Second, the time factor affects the size of the grains; once recrystallisation has occurred, prolonged heating causes growth in size of the grains. This will change a fine-grained structure to a coarse-grained structure and consequently the metal will become softer.

6.1.2. EFFECT OF HEAT ON MECHANICAL PROPERTIES OF STAINLESS STEEL ORTHODONTIC WIRE. It is a generally accepted fact that the elastic properties of formed orthodontic arch wire are improved by low-temperature heat treatment at 300 - 500°C for a short period. (Backofen and Gales)\(^{(4)}\), (Howe et al)\(^{(29)}\), (Ingerslev)\(^{(30)}\). This procedure is often referred to as hardening, stress relieving or, simply as heat treatment.
Its effect has been the subject of investigation at frequent intervals throughout the last few years.

In experiments in which wires, bent in a series of V-shapes were heat treated and subjected to tension, Funk\(^{(24)}\) found a marked improvement in the elastic properties, no such improvement was observed for treated straight wires subject to deflection.

Backofen and Gales\(^{(4)}\) who studied the expansion of U-shaped loops under tension, found a marked increase in the elastic strength after heat treatment.

Kemler\(^{(32)}\) concluded from an experiment on the expansion of uniform round loops of stainless steel that a low temperature heat treatment resulted in an increase in the proportional limit and elastic modulus.

In experiments on the proportional limit, tensile strength and hardness of austenitic stainless steel, Wilkinson\(^{(67)}\) found that the properties depended on the period of heat treatment and the temperature, and that annealing of the wire starts at 500\(^0\) C and since clinically satisfactory low-fusing solder melts in the range 650 — 750\(^0\) C, some softening must be expected when wire is soldered. He also found that for the range of temperatures and times selected, the hardness of the particular wire tested was directly proportional to its tensile strength.

Using 18-8 stainless steel wire coiled around a cylinder,
Mutchler(39) showed that heat treatment resulted in changes in proportional limit and the modulus of elasticity.

Delgado and Anderson(19) considered that the effect of low temperature heat treatment of 18-8 stainless steel, on tensile strength and capacity for bending is not great enough to be of use in clinical practice.

Ingerslev(30) in a series of experiments on formed archwires of 18-8 stainless steel found that heat treatment produced changes in elastic limit for expansion and compression of the arches and for deflection of straight segments of the same wire. He considers that changes in the elastic limit are due to resolution of the internal stresses introduced during the cold working of the wire and that archwires of the 18-8 stainless steel used should not be heated at 400°C or more as this considerably reduces the resistance to corrosion. The modulus of elasticity was not affected by the time-temperature combination used.

6.1.3. EXPERIMENTAL WIRE. The stainless steel wire used for experimental work was Remanit Dentaurum "spring hard", from the Dentaurum Company, Pforzheim, West Germany. The wire was purchased from the local agent. The manufacturer's catalogue(20) describes these wires as "being made from fine quality stainless steel, absolutely mouth acid-resistant and of outstanding tensile and yield strength and are highly resilient". The only figure quoted for this wire is that for ultimate tensile strength,
being 270 - 285 P.S.I.

A tensile test was carried out on straight lengths of this wire after being heat treated, using a Hounsfield Tensometer and two opposed Huggenburger strain gauges. The results were:

Reemanit Stainless Steel Wire (Spring Hard)
0.0385" diameter
Heat treated in a 3" diameter tube furnace for 10 minutes at 405° C.
Five tests
0.02% proof stress 190,000 ± 3.5% p.s.i.
(one high value disregarded)
Ultimate Tensile Strength
297,000 p.s.i. ± 1.2%
Youngs Modulus
26.2 x 10^6 p.s.i. ± 5.7%

6.2. COBALT CHROMIUM WIRE.

Relatively little comprehensive literature exists on the cobalt-nickel wire studied. The original manufacturer, the Elgin National Watch Company\(^{(59)}\), of Elgin, Illinois, claims that their cobalt-nickel wire "Elgiloy", combines the excellent strength characteristics and corrosion resistance of cobalt, the added corrosion resistance of chromium, and the strength and ductility of nickel. Molybdenum is added to increase the mechanical properties at elevated temperatures while the
remaining elements provide the additional properties of 
hardenability and set resistance. The nominal composition of 
"Elgiloy" is as follows:

Nominal Composition

Patented: U.S. Pat. No. 2524661

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>40%</td>
<td>Manganese</td>
<td>2%</td>
</tr>
<tr>
<td>Chromium</td>
<td>20%</td>
<td>Carbon</td>
<td>0.15%</td>
</tr>
<tr>
<td>Nickel</td>
<td>15%</td>
<td>Beryllium</td>
<td>0.04%</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>7%</td>
<td>Iron</td>
<td>Balance</td>
</tr>
</tbody>
</table>

In application the manufacturer claims the wire form of 
"Elgiloy" has demonstrated the following outstanding 
characteristics:

1. Less than 2% set as compared to 10% set for music wire in 
   identical long term tests.

2. Hysteresis loss of less than 1/10 of 1% in torsion bar 
   applications.

3. Less than 0.6% loss in load at 75,000 p.s.i. stress level 
   at 575°F in compression spring test.

4. Superior resistance to corrosive attack.

It is claimed that a 45-48% cold reduction results in optimum 
spring temper. This decision is based on securing the best 
shear strength properties coupled with the ductility necessary 
for proper forming and maximum spring characteristics. To 
obtain maximum properties this cold reduction is usually combined 
with heat treatment at 980°F after forming. It is not a true
precipitation hardening alloy since the amount of heat treatment is a function of the amount of cold work. Therefore, when "Elgiloy" is annealed, the cold work is removed and maximum properties cannot be regained by heat treatment. This combination of cold work and heat treatment will result in the following typical mechanical properties for "Elgiloy" wire.

- Ultimate Strength: 340,000 p.s.i.
- Yield Strength: 310,000 p.s.i.
- Shear Yield: 210,000 p.s.i.
- Modulus of Elasticity: 28,500,000 p.s.i.
- Torsional Modulus: 11,200,000 p.s.i.
- Hardness (Rockwell C): 51-55

Four forms of this wire are listed by the supplied, Rocky Mountain Dental Products Company(41), of Denver Colorado. These are:

1. R.M. Red High Spring Temper Elgiloy (Resilient)

   "Hard" wire with exceptionally high spring qualities. Not recommended for techniques involving sharp plier manipulation since it will only allow minimum work hardening.

2. R.M. Green Elgiloy (Semi-resilient)

   Spring temper is comparable to a good spring tempered steel wire. They can be shaped easily with fingers and allow for some plier manipulation before heat treating. However after heat treating they should not be adjusted sharply.
3. **R.M. Yellow Elgiloy (Ductile).**

This is relatively ductile and can be bent with fingers and pliers. It is difficult to solder smaller yellow "Elgiloy" wires. They should be heat treated for maximum resiliency and performance and can be adjusted slightly after heat treating.

4. **Blue Elgiloy (Soft).**

Soft and can be easily bent with fingers and pliers. Recommended when wire to be used is over 0.020" or when wire requires considerable shaping, welding or soldering. Should be heat treated for best results.

6.2.1. **HEAT TREATMENT.** The suppliers give the following information on how to heat treat "Elgiloy".

1. **R.M. Heat-Treat Unit and Tempering Paste.** Average heat-treat time is 30 seconds.

2. **R.M. Adapting Cables.** Place cable tips about $\frac{3}{4}$" apart on arch wire. Heat wire to straw colour. (Do not allow wire to become red hot, as this will anneal wire). Heat adjacent section and proceed along arch.

3. **Brush Flame.** Bring wire to deep red colour.

4. **Dental Oven.** 900°F for 7 - 12 minutes.

Mutchler\(^{39}\) investigated the effect of various time-temperature combinations on the mechanical properties of "Elgiloy" wire, and found that the wire is capable of exhibiting a significant improvement in its mechanical properties after heat treatment.
He concluded that:

1) Controlled heat treatment produces an increase in the proportional limit, modulus of elasticity and modulus of resilience.

2) The optimum heat treatment for the cobalt chromium wire studied (Elgiloy) is 3 to 15 minutes at a temperature of 900°F (482°C) to 1000°F (538°C).

3) Prolonged heating has no significant effect on the wire studied.

4) Temperatures of 1100°F (593°C) and 1200°F (649°C) produce no harmful effect in the cobalt chromium wire when heated for less than 3 minutes.

He did not heat the wire above 1200°F (649°C) and made no comment on heating above this temperature. He found that in all cases the modulus of elasticity was increased by approximately 20% when heated to 900°F and considers that the increase is not due to work hardening alone, but probably to some type of crystalline rearrangement during heat treatment which results in intramolecular attraction and that the constitution of the alloy may be varied sufficiently to provide a group of alloys with a range of mechanical properties.

6.2.2. EXPERIMENTAL WIRE. Brockhurst\(^{(7)}\) gives the following on "Elgiloy" yellow and "Elgiloy" blue.

"Elgiloy" Yellow. (See Fig. 21 for effect of heat treatment on yield point and ultimate strength, Fig. 22 for heat treatment, hardness.)
Figure 21.
Ultimate Tensile Strength and Yield Point after Heat Treatment of Cobalt Chromium (Yellow Elgiloy) and Nimonic 90 Wires.
Figure 22.

Hardness (D.P.N.) v Temperature of Cobalt Chromium (Blue and Yellow Elgiloy), Stainless Steel and Nimonic 90 Wires.
Yield stress as received 111,000 p.s.i. 0.02% yield
600°C for 1 min. 187,000 p.s.i.

Ultimate Tensile Strength
as received 228,000 p.s.i.
600°C for 1 min. 246,000 p.s.i.

Vickers Microindentation Hardness Number 300 gm. load
as received 484
600°C for 1 min. 592

Mechanical properties decrease rapidly after 800°C.

"Elgiloy" Blue
Yield stress as received 98,000 p.s.i. 0.02% yield
Ultimate Tensile Strength 218,000 p.s.i.
Hardness D.P.N. as received 450
650°C for 1 min. 576

6.3. **NIMONIC 90.** The nickel base alloy used in experimental work, Nimonic 90, an alloy of the wrought, heat resisting group of alloys. No comprehensive dental literature exists on the nickel base alloy studied. Available data is related to high temperature performance only. (Metals Handbook)\(^{(37)}\).

Nominal composition of Nimonic 90 alloy is (Metals Handbook)\(^{(37)}\):

- Carbon 0.1% max.
- Manganese 1.5% max.
- Silicon 1% max.
- Chromium 20%
<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>Remainder</td>
</tr>
<tr>
<td>Cobalt</td>
<td>16%</td>
</tr>
<tr>
<td>Titanium</td>
<td>2.50%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1.5%</td>
</tr>
<tr>
<td>Iron</td>
<td>5% max.</td>
</tr>
</tbody>
</table>

Some of the other alloys in this group are Hastelloy, Inconel, Waspaloy. The alloys are manufactured in all forms common to the industry; billets, sheet, tubing and wire. The nickel base alloys have achieved wide acceptance in aircraft applications, largely as a result of their suitability at elevated temperatures. The alloys containing aluminium are hardened by a single or double ageing treatment, being cooled from the range 1750 to 2150°F. Yield strength of 110,000 p.s.i. and ultimate tensile strength of 175,000 p.s.i. at 75°F were obtained after a heat treatment of air cooling from 1975°F, reheating to 1300°F, then air cooling.

The nickel base alloys are welded and soldered by the same procedures as are used for the series 300 stainless steels.

The nickel base wire used in experiments was obtained as a sample from Wright and Company, of Sydney, and was manufactured by Henry Wiggin and Company, Birmingham, England. The manufacturer (28) states that Nimonic 90 spring wire is available in the cold drawn hard condition or in the solution-treated condition. Cold drawn hard wire is supplied with a bright finish; wire in the solution treated condition has an oxidized
finish in sizes 0.104 in. diameter and larger, and a dull but clean finish in sizes below 0.104 in. diameter. Manufacturing procedures and mechanical properties are listed below (Tables 2 and 3).

For applications where severe cold forming is necessary, material in the solution treated condition should be specified, and after forming the components should be aged (4 hours 750°C).

6.3.1. EXPERIMENTAL WIRE. Brodhurst gives the following information on the wire used experimentally (see Fig. 21 for effect of heat treatment on yield stress and ultimate tensile strength; Fig. 22 for hardness.)

Nimonic 90 wire 0.036" diam. solution treated 30% cold drawn

<table>
<thead>
<tr>
<th></th>
<th>As received</th>
<th>142,000 p.s.i.</th>
<th>0.02% yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Stress</td>
<td>800°C for 1 min.</td>
<td>216,000 p.s.i.</td>
<td>0.02% yield</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As received</td>
<td>220,000 p.s.i.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>800°C for 1 min.</td>
<td>257,000 p.s.i.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Microindentation hardness 300 gm. load

<table>
<thead>
<tr>
<th></th>
<th>As received</th>
<th>363</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>800°C for 1 min.</td>
<td>470</td>
</tr>
</tbody>
</table>

Mechanical properties decrease rapidly after 850°C.

6.4. PLATINISED GOLD WIRE.

Crowell(17) stated that orthodontic fabrications require high strength and resistance to corrosion in the mouth and that both
<table>
<thead>
<tr>
<th>Service Temperature °C</th>
<th>Recommended Wire Form</th>
<th>Heat Treatment After Coiling</th>
<th>Service Condition of Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 350</td>
<td>Cold drawn hard spring temper</td>
<td>4 hours at 650°C air cooled</td>
<td>Direct-aged from cold-drawn</td>
</tr>
<tr>
<td>Above 350</td>
<td>Solution treated</td>
<td>4 hours at 750°C air cooled</td>
<td>Solution treated and aged</td>
</tr>
</tbody>
</table>
TABLE 3

Mechanical Properties - Nimonic 90 Spring Wire

<table>
<thead>
<tr>
<th></th>
<th>Solution Treated and Aged</th>
<th>Direct Aged from Cold Drawn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity in tension lb/sq.in. x 10^6 at 20°C</td>
<td>31</td>
<td>33 - 35</td>
</tr>
<tr>
<td>Limit of proportionality in tension lb/sq.in. x 10^3</td>
<td>72</td>
<td>130 - 140</td>
</tr>
</tbody>
</table>
requirements are met by the complex alloys based on gold and platinum. These alloys age-harden readily, and values for tensile strength and hardness may be obtained that are unusually high for non ferrous metals. The modulus of elasticity is of the order of 15 x 10^6 p.s.i. The composition limits in eight groups or types of modern dental gold alloy wires are given in Table 4, and some of the mechanical properties of these alloys are indicated in Table 5. Skinner\(^{(54)}\) and Wise\(^{(70)}\) described the nature of these alloys and their response to heat treatment. Wise\(^{(70)}\) believed that the art of age-hardening alloys originated with the precious metals, as it was observed as early as 1905 by the S.S. White Dental Manufacturing Co., that a gold, platinum, silver, copper alloy would harden upon cooling from red heat.

Skinner\(^{(54)}\) maintained that the directions of the manufacturer should be followed in heat treatment, particularly for age-hardening since the optional age-hardening temperature depends upon the composition of the alloy and it may be a narrow or broad range. He (Skinner)\(^{(55)}\) gave details on the general effects of constituents in dental gold alloy wires.

Bush, Taylor and Peyton\(^{(15)}\) compared the mechanical properties, chemical compositions and microstructures of dental gold wires. Some of their conclusions were:

1. A definite correlation exists between the hardness and tensile strength of wrought gold alloys of varying chemical
## TABLE 4.

Composition Limits of High-Strength Precious Metal Wires used in Dentistry*

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Au</th>
<th>Pt</th>
<th>Pd</th>
<th>Ag</th>
<th>Cu</th>
<th>Ni</th>
<th>Zn</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25-30</td>
<td>40-50</td>
<td>25-30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Platinum</td>
</tr>
<tr>
<td>2</td>
<td>54-60</td>
<td>14-18</td>
<td>1-8</td>
<td>7-11</td>
<td>11-14</td>
<td>1 max.</td>
<td>2 max.</td>
<td>Platinum</td>
</tr>
<tr>
<td>3</td>
<td>45-50</td>
<td>8-12</td>
<td>20-25</td>
<td>5-8</td>
<td>7-12</td>
<td>-</td>
<td>1 max.</td>
<td>Platinum</td>
</tr>
<tr>
<td>4</td>
<td>62-64</td>
<td>7-13</td>
<td>6 max.</td>
<td>9-16</td>
<td>7-14</td>
<td>2 max.</td>
<td>1 max.</td>
<td>Light Gold</td>
</tr>
<tr>
<td>5</td>
<td>54-70</td>
<td>2-7</td>
<td>5 max.</td>
<td>9-15</td>
<td>12-18</td>
<td>2 max.</td>
<td>1 max.</td>
<td>Gold</td>
</tr>
<tr>
<td>6</td>
<td>56-63</td>
<td>5 max.</td>
<td>5 max.</td>
<td>14-25</td>
<td>11-18</td>
<td>3 max.</td>
<td>1 max.</td>
<td>Gold</td>
</tr>
<tr>
<td>7</td>
<td>10-28</td>
<td>25 max.</td>
<td>20-37</td>
<td>6-30</td>
<td>14-21</td>
<td>2 max.</td>
<td>2 max.</td>
<td>Platinum</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>1 max.</td>
<td>42-44</td>
<td>38-41</td>
<td>16-17</td>
<td>1 max.</td>
<td>-</td>
<td>Platinum</td>
</tr>
</tbody>
</table>

(a) Fractional Percentages of Iridium, Indium and Rhodium are omitted here.

TABLE 5.
Some Physical and Mechanical Properties of High-Strength Precious Wires used in Dentistry

<table>
<thead>
<tr>
<th>Alloy (a)</th>
<th>Tensile Strength 1000 p.s.i.</th>
<th>Proportional Limit 1000 p.s.i.</th>
<th>Elongation % (8 in gauge)</th>
<th>B.H.N.(e)</th>
<th>Fusion Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soft</td>
<td>Hardened</td>
<td>Soft</td>
<td>Hardened</td>
<td>Soft</td>
</tr>
<tr>
<td>1.</td>
<td>125-180</td>
<td>g</td>
<td>80-150</td>
<td>g</td>
<td>14-15</td>
</tr>
<tr>
<td>2.</td>
<td>110-130</td>
<td>160-186</td>
<td>72-102</td>
<td>130-151</td>
<td>12-22</td>
</tr>
<tr>
<td>3.</td>
<td>140-150</td>
<td>160-190</td>
<td>110-120</td>
<td>130-140</td>
<td>8-10</td>
</tr>
<tr>
<td>4.</td>
<td>90-115</td>
<td>120-165</td>
<td>55-80</td>
<td>85-140</td>
<td>14-26</td>
</tr>
<tr>
<td>5.</td>
<td>82-120</td>
<td>130-165</td>
<td>53-73</td>
<td>103-139</td>
<td>14-20</td>
</tr>
<tr>
<td>6.</td>
<td>84-100</td>
<td>96-157</td>
<td>52-58</td>
<td>10-124</td>
<td>20-28</td>
</tr>
</tbody>
</table>

(a) See Table 4 for chemical compositions of alloys.
(g) Not appreciably affected by Heat Treatment.
compositions.

2. A similar correlation exists between the proportional limits and tensile strengths of alloys which can be expressed as a ratio of the one to the other, for example, proportional limit equals 2/3 tensile strength.

3. A linear relationship exists between the proportional limit in bending and diamond pyramid hardness. A similar relationship exists between proportional limit in bending and ultimate tensile strength.

6.4.1. EXPERIMENTAL WIRE. The precious metal wire used experimentally was a Type 2 alloy (Table 4), Ney-Oro Elastic 12, manufactured by the J.M. Ney Company, Maplewood Ave., Bloomfield, Conn., U.S.A. and purchased from a local dental supply house.

The manufacturer[60] gives the following physical properties for the wire chosen.

**Ney Wire Oro Elastic No.12**

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Fusion Temperature</th>
<th>2010°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional Limit</td>
<td>Soft 88,000 p.s.i.</td>
<td>135,000 p.s.i.</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>125,000 lb./sq.in.</td>
<td>178,000 lb./sq.in.</td>
</tr>
<tr>
<td>Elongation</td>
<td>20%</td>
<td>15%</td>
</tr>
<tr>
<td>Brinell Hardness Number</td>
<td>(B.H.N.) 175</td>
<td>275</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>12.1 gm/cc.</td>
<td></td>
</tr>
</tbody>
</table>
The wire is supplied from the factory fully annealed (manufacturers claim), having had all work hardness removed after the final drawing operation. "To produce sufficient hardness for most ordinary requirements, the appliance can simply be allowed to cool in the air after soldering." (Manufacturer)\(^{(60)}\). If a greater hardening effect is desired, it should be placed in a controlled furnace at 900\(^{\circ}\)F and allowed to cool from that temperature to 450\(^{\circ}\)F. in fifteen minutes.
CHAPTER 7.

METHOD

The experiments were carried out on the wires listed in Table 6, which were obtained from local (dental) suppliers, with the exception of the nickel base alloy which was supplied by courtesy of manufacturer's agent (Wright and Company Pty. Ltd., Alexandria, N.S.W.).

7.1. FABRICATION OF ARCHES

The wires were obtained in straight lengths with the exception of the Nimonic 90 and stainless steel wires which were in coil form. The wires were cut into 150 mm. lengths, and at one end of each length a round loop 2.5 to 3.5 mm. in diameter was bent using loop forming pliers. To obtain a shape comparable with a finished orthodontic upper lingual expansion arch, a standard arch former was used (Figures 23 and 24).

The end loop was placed over a fixed pin (P. Figure 24) and the wire placed so that it rested in a horizontal groove in a stationary cylinder (I. Figure 24). On top of this was then placed a rotating tube part with a vertical pin to keep the wire in the groove; when rotating this top part of the arch former the wire was carried around the groove so that the straight length of wire remaining rested along the straight line C D. (Figure 24). The second stationary cylinder was then inserted in the
Figure 23.

Standard Arch Former
Figure 24. Dimensions Standard Arch Former.

Figure 25. Determination of 0.5% (Width of Arch) Proof Load of Standard Arches
base of the arch former, the above procedure repeated so that the remaining straight length of arch wire rested along the line E F (Figure 24), the third cylinder was then inserted, procedure repeated so that remaining straight length was parallel to G H. The looped end was then removed from the pin, rotating part placed on cylinder I and this end of the wire made parallel to A B.

With the wire remaining on the arch former scratch marks were made at points I and J and the excess wire at points A and H cut off using a separating disc. The arch was then removed from the arch former (after removal of cylinders II and III and grooves were cut on the inner surfaces of the wire at points I and J, to a depth of approximately 0.2 mm. The rotations were identical for each wire, thus ensuring minimum variation in the shape of the arches, and the inner grooves (which were used to attach the arch to measuring apparatus) were cut at a point taken from a line on the standard arch former.

7.2. **HEAT TREATMENT**

Ten archwires were made from each type of wire examined and these were heat-treated in a 3 in. diameter tube furnace using a Chromel-Alumel thermocouple indicating temperature to $+5^\circ$ C, and controlled to $+5^\circ$ C. Time-temperature combinations for
heat treatment are given in Table 7. The standard arches were numbered 1 to 10 for each arch of each material.

7.3. **APPARATUS**

The wires were then subjected to loads in a specifically designed apparatus (Figure 26). The apparatus was tested by loading without specimens to 2,000 gms. - no variation in the suspension part of the apparatus was observed.

7.4. **WIDTH OF STANDARD ARCHES**

Before any loads were applied to the arch wires the distance between the outer surfaces of the arch wire opposite the grooves I and J were measured using this apparatus and this distance was termed the standard arch width.

7.5. **LOAD v DEFLECTION.**

Loads were applied in fifty gram increments and a reading of the expansion produced taken. The first reading was taken at 50 gms.

A Cambridge Cathetometer was used to measure the deflection after each load increment and the last reading taken when it became quite obvious that the proof load of the spring had been exceeded.

7.6. **DIAMETER OF WIRES**

The diameters of the wires used were measured using a screw micrometer by taking five readings around each arch wire.
Figure 26.
Apparatus, Load-Deflection Readings.
TABLE 6.
Wires Examined

<table>
<thead>
<tr>
<th>Material</th>
<th>Nominal Diameter (inches)</th>
<th>Manufacturers Name and Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>0.036</td>
<td>Stainless Steel, Remanit Dentaurum. (20)</td>
</tr>
<tr>
<td>Cobalt Chromium Alloy B</td>
<td>0.036</td>
<td>Blue Elgiloy, The Elgin National Watch Company. (59)</td>
</tr>
<tr>
<td>Cobalt Chromium Alloy Y</td>
<td>0.036</td>
<td>Yellow Elgiloy, The Elgin National Watch Company. (59)</td>
</tr>
<tr>
<td>Nimonic 90</td>
<td>0.036</td>
<td>Nimonic 90, Henry Wiggins and Company Ltd. (28)</td>
</tr>
<tr>
<td>Platinised Gold</td>
<td>0.036</td>
<td>Ney Oro Elastic No.12, The J.M. Ney Company. (60)</td>
</tr>
</tbody>
</table>

TABLE 7.
Heat Treatment - Time - Temperature Combinations of Materials Tested

<table>
<thead>
<tr>
<th>Material</th>
<th>Time (in minutes)</th>
<th>Temperature °C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>10</td>
<td>392</td>
</tr>
<tr>
<td>Cobalt Chromium Y and B</td>
<td>12</td>
<td>482</td>
</tr>
<tr>
<td>Nimonic 90</td>
<td>3</td>
<td>500</td>
</tr>
<tr>
<td>Platinised Gold</td>
<td>3</td>
<td>482 then allowed to cool to 232 over 15 minutes</td>
</tr>
</tbody>
</table>
CHAPTER 8.

RESULTS.

The results of the investigation are shown in Tables 8, 9, 10, 11 and Figure 27.

8.1. LOAD v DEFLECTION.

Load v deflection readings are given in the appendix. For each material the mean deflection per fifty gram increment was calculated and the mean load deflection curves of the materials examined are shown in Figure 27. (It is noticed that the steepness of the curves differ).

8.2. DIAMETER OF WIRES

The mean of five readings for each wire are shown in Table 8. The overall mean with standard deviation and coefficient of variation are shown for the different wires used.

The wires used were of a nominal diameter of 0.036 inches (0.9144 mm.) and were found to be uniformly round and of diameters given in Table 8.

8.3. WIDTH OF STANDARD ARCHES.

The width of the standard arches are shown in Table 9. (Width of arch wire has been defined as the width of the arch wire between points I and J, on the outer surfaces of the archwire opposite the grooves at I and J.). Means, standard deviation,
TABLE 8.

Diameter (Millimeters) of Wire Used for Standard Arches
(mean of five readings for each wire)

<table>
<thead>
<tr>
<th>Number</th>
<th>Material</th>
<th>Platinised Gold Wire</th>
<th>Nimonic 90</th>
<th>Stainless Steel Wire</th>
<th>Cobalt Chromium Wire Y</th>
<th>Cobalt Chromium Wire B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td>0.9144</td>
<td>0.9144</td>
<td>0.8864</td>
<td>0.9067</td>
<td>0.9093</td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td>0.0118</td>
<td>0.9169</td>
<td>0.8864</td>
<td>0.9067</td>
<td>0.9093</td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td>0.9118</td>
<td>0.9118</td>
<td>0.8864</td>
<td>0.9067</td>
<td>0.9093</td>
</tr>
<tr>
<td>4.</td>
<td></td>
<td>0.9118</td>
<td>0.9144</td>
<td>0.8864</td>
<td>0.9067</td>
<td>0.9093</td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td>0.9118</td>
<td>0.9144</td>
<td>0.8864</td>
<td>0.9067</td>
<td>0.9118</td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td>0.9118</td>
<td>0.9169</td>
<td>0.8864</td>
<td>0.9067</td>
<td>0.9093, 0.9093</td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td>0.9118</td>
<td>0.9164</td>
<td>0.8864</td>
<td>0.9067</td>
<td>0.9093</td>
</tr>
<tr>
<td>8.</td>
<td></td>
<td>0.9144</td>
<td>0.9169</td>
<td>0.8864</td>
<td>0.9067</td>
<td>0.9093</td>
</tr>
<tr>
<td>9.</td>
<td></td>
<td>0.9118</td>
<td>0.9169</td>
<td>0.8864</td>
<td>0.9093</td>
<td>0.9093</td>
</tr>
<tr>
<td>10.</td>
<td></td>
<td>0.0118</td>
<td>0.9144</td>
<td>0.8864</td>
<td>0.9093</td>
<td>0.9118</td>
</tr>
</tbody>
</table>

Mean: 0.9123 0.9154 0.8864 0.9072 0.9098

Standard Deviation: 0.001 0.002 - 0.0001 0.001

Coefficient of Variation: 0.1 0.2 - 0.01 0.1
<table>
<thead>
<tr>
<th>Number</th>
<th>Platinised Gold Wire</th>
<th>Nimonic 90</th>
<th>Stainless Steel Wire</th>
<th>Cobalt Chromium Wire X</th>
<th>Cobalt Chromium Wire B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>43.46</td>
<td>43.61</td>
<td>43.93</td>
<td>45.66</td>
<td>45.22</td>
</tr>
<tr>
<td>2.</td>
<td>43.89</td>
<td>43.36</td>
<td>44.34</td>
<td>45.22</td>
<td>44.79</td>
</tr>
<tr>
<td>3.</td>
<td>43.27</td>
<td>44.11</td>
<td>44.11</td>
<td>45.43</td>
<td>44.53</td>
</tr>
<tr>
<td>4.</td>
<td>43.60</td>
<td>43.87</td>
<td>43.46</td>
<td>45.93</td>
<td>44.76</td>
</tr>
<tr>
<td>5.</td>
<td>43.61</td>
<td>42.82</td>
<td>44.00</td>
<td>45.61</td>
<td>45.02</td>
</tr>
<tr>
<td>6.</td>
<td>43.52</td>
<td>43.03</td>
<td>43.29</td>
<td>45.53</td>
<td>44.99</td>
</tr>
<tr>
<td>7.</td>
<td>43.18</td>
<td>43.94</td>
<td>44.49</td>
<td>45.19</td>
<td>45.91</td>
</tr>
<tr>
<td>8.</td>
<td>43.53</td>
<td>44.12</td>
<td>43.77</td>
<td>44.80</td>
<td>44.44</td>
</tr>
<tr>
<td>9.</td>
<td>43.81</td>
<td>43.41</td>
<td>43.88</td>
<td>45.53</td>
<td>44.95</td>
</tr>
<tr>
<td>10.</td>
<td>43.63</td>
<td>43.35</td>
<td>43.09</td>
<td>45.26</td>
<td>45.76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>43.55</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.22</td>
</tr>
<tr>
<td>Coefficient of Variation %</td>
<td>0.5</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.07</td>
</tr>
</tbody>
</table>
TABLE 10.

0.5% (Width of Arch) Proof Load (Gms.) of Standard Arches After Heat Treatment at Various Time-Temperature Combinations

<table>
<thead>
<tr>
<th>Number</th>
<th>Platinised Gold Wire</th>
<th>Nimonic 90</th>
<th>Stainless Steel Wire</th>
<th>Cobalt Chromium Wire Y</th>
<th>Cobalt Chromium Wire B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>800</td>
<td>1000</td>
<td>950</td>
<td>820</td>
<td>730</td>
</tr>
<tr>
<td>2.</td>
<td>750</td>
<td>970</td>
<td>940</td>
<td>810</td>
<td>680</td>
</tr>
<tr>
<td>3.</td>
<td>770</td>
<td>1050</td>
<td>920</td>
<td>850</td>
<td>730</td>
</tr>
<tr>
<td>4.</td>
<td>750</td>
<td>1030</td>
<td>950</td>
<td>850</td>
<td>690</td>
</tr>
<tr>
<td>5.</td>
<td>780</td>
<td>1010</td>
<td>930</td>
<td>800</td>
<td>760</td>
</tr>
<tr>
<td>6.</td>
<td>795</td>
<td>1000</td>
<td>950</td>
<td>800</td>
<td>760</td>
</tr>
<tr>
<td>7.</td>
<td>780</td>
<td>1020</td>
<td>950</td>
<td>800</td>
<td>720</td>
</tr>
<tr>
<td>8.</td>
<td>800</td>
<td>970</td>
<td>960</td>
<td>810</td>
<td>720</td>
</tr>
<tr>
<td>9.</td>
<td>770</td>
<td>1000</td>
<td>970</td>
<td>830</td>
<td>720</td>
</tr>
<tr>
<td>10.</td>
<td>810</td>
<td>1030</td>
<td>950</td>
<td>800</td>
<td>730</td>
</tr>
<tr>
<td>Mean</td>
<td>780</td>
<td>1008</td>
<td>947</td>
<td>817</td>
<td>724</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>20.9</td>
<td>25.7</td>
<td>14.2</td>
<td>20.0</td>
<td>25.5</td>
</tr>
<tr>
<td>Coefficient of Variation %</td>
<td>2.7</td>
<td>2.5</td>
<td>1.5</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Standard Error</td>
<td>6.6</td>
<td>8.1</td>
<td>4.5</td>
<td>6.2</td>
<td>8.1</td>
</tr>
</tbody>
</table>
TABLE 11.

Spring Rate (Grams per Millimetre) of Standard Arches After Heat Treatment at Various Time-Temperature Combinations

<table>
<thead>
<tr>
<th>Number</th>
<th>Platinised Gold Wire</th>
<th>Nimonic 90</th>
<th>Stainless Steel Wire</th>
<th>Cobalt Chromium Wire Y</th>
<th>Cobalt Chromium Wire B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>48.49</td>
<td>88.90</td>
<td>59.88</td>
<td>76.58</td>
<td>79.64</td>
</tr>
<tr>
<td>2.</td>
<td>50.95</td>
<td>89.30</td>
<td>60.60</td>
<td>76.26</td>
<td>79.29</td>
</tr>
<tr>
<td>3.</td>
<td>50.00</td>
<td>88.48</td>
<td>60.98</td>
<td>77.41</td>
<td>80.00</td>
</tr>
<tr>
<td>4.</td>
<td>49.66</td>
<td>88.90</td>
<td>60.98</td>
<td>77.57</td>
<td>78.59</td>
</tr>
<tr>
<td>5.</td>
<td>49.08</td>
<td>86.96</td>
<td>59.88</td>
<td>74.37</td>
<td>80.00</td>
</tr>
<tr>
<td>6.</td>
<td>49.39</td>
<td>86.58</td>
<td>60.24</td>
<td>77.57</td>
<td>75.93</td>
</tr>
<tr>
<td>7.</td>
<td>48.49</td>
<td>90.10</td>
<td>60.98</td>
<td>75.63</td>
<td>88.81</td>
</tr>
<tr>
<td>8.</td>
<td>50.00</td>
<td>88.90</td>
<td>59.53</td>
<td>80.72</td>
<td>77.57</td>
</tr>
<tr>
<td>9.</td>
<td>50.31</td>
<td>89.30</td>
<td>60.24</td>
<td>77.57</td>
<td>76.91</td>
</tr>
<tr>
<td>10.</td>
<td>49.39</td>
<td>89.30</td>
<td>60.98</td>
<td>78.25</td>
<td>77.23</td>
</tr>
</tbody>
</table>

Mean 49.58  88.67  60.43  77.19  79.40

Standard Deviation 0.78  1.09  0.55  1.69  3.59

Coefficient of Variation % 1.6  1.2  0.9  2.2  4.5

Standard Error 0.25  0.35  0.17  0.53  1.14
Figure 27.

Load Deflection Curves of Standard Arches after Heat Treatment at Various Time-Temperature Combinations

Note: Initial reading taken with a load of 50 grams.
coefficient of variation and standard error of the mean were calculated for each different wire used.

Mutchler(39) reported that both the cobalt chromium and chromium nickel wires used in his experiments showed some tendency to return to their original form. Provided the form of the arch is otherwise similar, this difference after heat treatment would not alter spring rate and allowance is made for any error in proof load by taking the proof load as the 0.5% (width of arch) proof load.

8.4 PROOF LOAD

The 0.5% (width of arch) proof loads are shown in Table 10. Mean, standard deviation, coefficient of variation and standard error were calculated for each material.

The 0.5% (width of archwire) proof load was determined by plotting the load deflection curve for each arch of each material, e.g. Figure 25. A typical stress-strain curve was obtained and an offset of 0.5% of the initial width of the arch (i.e. 0.22 mm. in example) was drawn parallel to the straight line position of the curve to intersect the curve at point P and this load was then taken as the 0.5% (width of arch) proof load.

The results obtained are significantly different for the materials used. The results are indicative of the proportional
limit in bending of the materials studied after heat treatment at various time-temperature combination (Table 7).

8.5. **SPRING RATE.**

The spring rates of the arches for the materials investigated are shown in Table 11.

The spring-rate or load-deflection rate was taken as the ratio of load to deflection for the straight line portion of the load-deflection curve.

This ratio was taken directly from each load deflection curve as in Figure 25, and the results are given in Table 11.

The mean, standard deviation, coefficient of variation and standard error were calculated for each material.

The varying spring rates are indicative of the moduli of elasticity of the alloys examined after heat-treatment at various time-temperature combinations (Table 7). The differences in spring rate of the standard arches of Nimonic 90, platinised gold, stainless steel and the cobalt chromium wires examined are statistically significant as their mean spring rates vary by more than two standard deviations either side of their respective means.

A "t" test was used to determine the significance of the
different spring rates of standard arches of cobalt chromium Y and B alloys.

The results of this test are given below and indicate that the difference in spring rate is not statistically significant.

Results of "t" test for difference in spring rate for standard arches of cobalt chromium Y and B after heat treatment at the same temperature time combination.

Difference between means $79.40 - 77.19 = 2.21$.

Standard Error of the Difference.

$$(1.14)^2 + (0.95)^2 = 1.48$$

"t" ratio $\frac{2.21}{1.48} = 1.5$

Interpretation using these "t" tables gives a value of $P$ greater than 0.05, indicating that the difference in spring rate is not statistically significant.
CHAPTER 9.

DISCUSSION.

The results from Tables 10 and 11 show that for the wires compared (of nominal diameter 0.036") the platinised gold wire results in the standard arch with the lowest spring rate. Also this material gives a standard arch with a comparatively high proof load.

However, from sections:

2.4 Deflection of Beams.
2.3 Stresses due to Bending
4. General Considerations of Orthodontic Spring Design

it is obvious that relatively small increases or decreases in the cross-section of wires used for orthodontic springs bring about quite large variations in the spring rate and proof load of these springs. Specifically, for springs constructed of round wire the spring rate is proportional to the diameter to the fourth power.

\[ \text{Spring rate } \propto d^4 \quad \text{or spring rate } = K_1 d^4 \quad \ldots \quad (35) \]

and proof load is proportional to the diameter cubed.

\[ \text{Proof load } \propto d^3 \quad \text{or proof load } = K_2 d^3 \quad \ldots \quad (36) \]

where \( K_1 \) and \( K_2 \) are constants (not the same) depending on the mechanical properties of the material, type of loading, general character and method of support of the spring.
9.1. **Comparison of Results**

Using equations 35 and 36, the mean results from Tables 10 and 11, the values of $K_1$ and $K_2$ were calculated. Assuming that the mechanical properties of the materials used remain the same for small changes in diameter, the values of $K_1$ and $K_2$ were calculated and comparison tables were calculated, (Tables 17 and 18), when the diameter of the materials used were changed to give standard arches with

(i) The same spring rate.

(ii) The same proof load.

These tables were calculated as follows:-

For each material the values of $K_1$ and $K_2$ were calculated (Tables 12 and 13) using the mean results from Tables 10 and 11.

For each measurement in each material the value of $K_1$ was substituted and the proof load calculated. A Chi-Square test was then made for differences between observed and calculated loads, e.g. Nimonic 90 Table 14.

Similarly differences between observed and calculated proof loads for other alloys investigated were tested using the Chi-Square test. Results are given in Table 15. Similarly for each measurement in each material the value of $K_2$ was substituted and the theoretical spring rate calculated.

A Chi-Square test was made for differences between calculated and observed spring rates. Results are given in Table 16.
**Table 12**

Calculated Values of $K_1$ (a constant) for Different Alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$K_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinised Gold Wire</td>
<td>1026</td>
</tr>
<tr>
<td>Nimonic 90</td>
<td>1314</td>
</tr>
<tr>
<td>Stainless Steel Wire</td>
<td>1360</td>
</tr>
<tr>
<td>Cobalt Chromium Wire Y</td>
<td>1094</td>
</tr>
<tr>
<td>Cobalt Chromium Wire B</td>
<td>961</td>
</tr>
</tbody>
</table>
### Table 13

**Calculated Values of $K_2$ (a constant) for Different Alloys**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$K_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinised Gold Wire</td>
<td>71.58</td>
</tr>
<tr>
<td>Nimonic 90</td>
<td>126.28</td>
</tr>
<tr>
<td>Stainless Steel Wire</td>
<td>97.89</td>
</tr>
<tr>
<td>Cobalt Chromium Wire Y</td>
<td>113.96</td>
</tr>
<tr>
<td>Cobalt Chromium Wire B</td>
<td>115.89</td>
</tr>
</tbody>
</table>
**TABLE 14**

Observed and Calculated Proof Loads for Standard Arches of Nimonic 90 Wire After Heat Treatment at 500°C for 3 minutes

<table>
<thead>
<tr>
<th>Number</th>
<th>Proof Load (Gms)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed 0</td>
<td>Calculated T</td>
<td>((O-T)^2/T)</td>
</tr>
<tr>
<td>1.</td>
<td>1000</td>
<td>1005</td>
<td>0.0248</td>
</tr>
<tr>
<td>2.</td>
<td>970</td>
<td>1013</td>
<td>1.9061</td>
</tr>
<tr>
<td>3.</td>
<td>1050</td>
<td>996</td>
<td>2.7771</td>
</tr>
<tr>
<td>4.</td>
<td>1030</td>
<td>1005</td>
<td>0.6067</td>
</tr>
<tr>
<td>5.</td>
<td>1010</td>
<td>1005</td>
<td>0.0247</td>
</tr>
<tr>
<td>6.</td>
<td>1000</td>
<td>1013</td>
<td>1.0169</td>
</tr>
<tr>
<td>7.</td>
<td>1020</td>
<td>1013</td>
<td>0.0480</td>
</tr>
<tr>
<td>8.</td>
<td>1000</td>
<td>1013</td>
<td>0.1690</td>
</tr>
</tbody>
</table>

\[ x^2 = 8.086 \]
### Differences Between Observed and Calculated Proof Loads of Different Alloys after Heat Treatment at Various Time Temperature Combinations

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$x^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinised Gold Wire</td>
<td>4.88</td>
</tr>
<tr>
<td>Nimonic 90</td>
<td>8.09</td>
</tr>
<tr>
<td>Stainless Steel Wire</td>
<td>1.91</td>
</tr>
<tr>
<td>Cobalt Chromium Wire Y</td>
<td>4.33</td>
</tr>
<tr>
<td>Cobalt Chromium Wire B</td>
<td>7.47</td>
</tr>
</tbody>
</table>
### TABLE 16

Differences Between Observed and Theoretical Spring Rates of Standard Arches After Heat Treatment at Various Time Temperature Combinations

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$x^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinised Gold Wire</td>
<td>.531</td>
</tr>
<tr>
<td>Nimonic 90</td>
<td>.013</td>
</tr>
<tr>
<td>Stainless Steel Wire</td>
<td>.045</td>
</tr>
<tr>
<td>Cobalt Chromium Wire Y</td>
<td>.335</td>
</tr>
<tr>
<td>Cobalt Chromium Wire B</td>
<td>.314</td>
</tr>
</tbody>
</table>
From \( x^2 \) table, the value of \( x^2 \) at \( P = .90 \) for nine degrees of freedom is 4.168 indicating that the differences between observed and calculated spring rates are not significant and that the mean results from Table 11 can be used for further calculations. From \( x^2 \) table of value of \( x^2 \) at \( P = 0.5 \) for nine degrees of freedom is 8.343 indicating that the differences between observed and calculated proof loads are not considered to be statistically significant and that mean results from Table 10 can be used for further calculations.

Using values of \( K_1 \) and \( K_2 \) (which were shown to be satisfactory by the Chi-Square test), and assuming that all factors (e.g., modulus of elasticity, proportional limit in bending, arch form) except diameter of wire used to form arches, remained constant, the theoretical diameters of similar standard arches of the alloys used were calculated to give standard arches of

(a) the same spring rates

(b) the same proof load

the results are given in Table 17 and 18.

From Table 17 it can be seen that if the diameters of the wires used to form the standard arches are changed the stainless steel and platinised gold arches will have the lowest spring rates and the arch with the highest spring rate is of cobalt chromium B. (Assuming no changes in mechanical properties of wires with variation in diameter.)
TABLE 17

Comparison of Standard Arches of Different Alloys with the Same Spring Rate after Heat Treatment at Various Time Temperature Combinations

<table>
<thead>
<tr>
<th>Material</th>
<th>Platinised Gold</th>
<th>Nimonic 90</th>
<th>Stainless Steel</th>
<th>Cobalt Chromium Y</th>
<th>Cobalt Chromium B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring Rate grams/mm.</td>
<td>49.58</td>
<td>49.58</td>
<td>49.58</td>
<td>49.58</td>
<td>49.58</td>
</tr>
<tr>
<td>Diameter of Wire (mm.)</td>
<td>0.9123</td>
<td>0.7915</td>
<td>0.8435</td>
<td>0.8120</td>
<td>0.8087</td>
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<tr>
<td>Proof Load grams</td>
<td>780</td>
<td>651</td>
<td>816</td>
<td>586</td>
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</tbody>
</table>
**TABLE 16**

Comparison of Standard Arches of Different Alloys with the Same Proof Load

*After Heat Treatment at Various Time Temperature Combinations*

<table>
<thead>
<tr>
<th>Material</th>
<th>Platinised Gold</th>
<th>Nimonic 90</th>
<th>Stainless Steel</th>
<th>Cobalt Chromium Y</th>
<th>Cobalt Chromium B</th>
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<tr>
<td>Proof Load (grams)</td>
<td>780</td>
<td>780</td>
<td>780</td>
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<td>780</td>
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<td>Diameter of Wire (mm)</td>
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<tr>
<td>Spring Rate Grams (mm)</td>
<td>49.58</td>
<td>62.96</td>
<td>46.62</td>
<td>72.58</td>
<td>87.68</td>
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</table>
9.2 CLINICAL SIGNIFICANCE OF RESULTS

In terms of efficiency of the appliance, the most suitable materials (of those compared) are the platinised gold and stainless steel. i.e. they have the greatest ranges of action for a given proof load. The least suitable material is the Blue Elgiloy.

Stainless steel wire has several disadvantages when used for expansion arches. These are:-

(1) Stainless Steel Wire is supplied in the hard drawn condition and these is some difficulty in constructing the appliance.

(2) Heat treatment is critical and must be carried out in a controlled furnace or dental oven. Heating over 400°C decreases the corrosion resistance (Ingerslev)\(^{(30)}\) and annealing of the wire starts at 600 - 650°C and since clinically satisfactory low fusing solder melts in the range 650 - 750°C some softening of the wire must be expected if the wire is soldered (Wilkinson)\(^{(67)}\).

Platinised gold wire has a spring rate (after heat treatment) comparable to that of heat treated stainless steel for equivalent proof loads (wire must be of larger diameter), and has the advantage that the wire is supplied in an annealed condition (making fabrication of appliances easy) and the appliance can be heat treated after gold soldering. The
The disadvantage of platinised gold wire for this type of appliance is that for the wire to obtain its maximum mechanical properties it must be heat-treated in a controlled furnace or dental oven; i.e. experimental wire $900^\circ F$ and allowed to cool from that temperature to $450^\circ F$ in fifteen minutes.

The cobalt chromium wires B and Y give high spring rates for standard arches for equivalent proof loads. Standard arch of cobalt chromium B has a spring rate almost double that of a standard arch of heat treated stainless steel or platinised gold. Mutchler(39) observed that this material can be heated at $650^\circ$ for a period of up to three minutes without seriously affecting its mechanical properties. Brookhurst(7), (Figure 21) shows that the proportional limit of cobalt chromium Y decreases when heated above $600^\circ C$. These results indicate that while this material can be soldered clinically, care must be taken not to overheat, or to heat for too long a period otherwise some softening of the wire will result.

The Nimonic 90 wire gives a standard arch with spring rate, 20-25% greater than stainless steel or platinised gold for the equivalent proof load.

However this alloy has two distinct advantages:

(a) As supplied it is relatively ductile.

(b) It can be heated over a wide range of temperatures ($300^\circ - 800^\circ$ (within the orthodontic soldering range) without
seriously affecting its mechanical properties. Heating within this range also produces hardening of the wire.

These two factors make this alloy very acceptable clinically and although not quite as good as stainless steel where high proof loads are required, this would be the most suitable of the materials studied for upper lingual expansion arches.
CHAPTER 10.

SUMMARY AND CONCLUSIONS

(1) The relevant spring properties (proof load and spring rate), of a nickel base alloy wire, Nimonic 90, are compared with those of (i) a stainless steel alloy
(ii) a platinised gold alloy
(iii) a cobalt chromium alloy
when bent in a structural form similar to the upper lingual expansion arch.

(2) Of the materials compared the stainless steel and the platinised gold alloy wires have the better spring properties after heat treatment.

(3) The cobalt chromium wire studied has the least desirable spring properties of the materials compared after heat treatment.

(4) The spring properties of the nickel base alloy wire studied are not as good as those of the platinised gold (20% less) or stainless steel alloy (25% less) wires used for comparative purposes but are significantly better than those of the cobalt chromium alloys (10% better than Y, 22% better than B) studied, after heat treatment.

(5) The nickel base alloy examined (Nimonic 90) which was initially selected from a number of high strength chromium-
protected alloy wires for partial denture clasp
construction by gold soldering (Brockhurst)\(^{(7)}\), should,
by virtue of its
(i) relatively good spring properties (due to a high
    proportional limit after heat treatment)
(ii) high ductility before heat treatment
(iii) wide range and high temperatures for heat treatment,
should be a suitable material for use in upper lingual
expansion appliances.
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65. Ibid. p 1.


APPENDIX
Load Deflection Readings, Platinised Gold Standard Archwires
after Heat Treatment at 482°C for 3 Minutes, Then Allowed
to cool to 232°C over 15 minutes

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* Deflection /50 gms.
ϕ Total Deflection.
### Load Deflection Readings, Stainless Steel Standard Archwires

*after Heat Treatment at 392°C for 10 minutes*

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* *Deflection @50 gms.*

\* Total Deflection.
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* Deflection at 50 gms.
\* Total Deflection.
### Load Deflection Readings, Cobalt Chromium/Standard Archwires

**After Heat Treatment at 482° C for 12 Minutes**

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* Deflection / 50 gms.

Φ Total Deflection.
Load Deflection Readings, Cobalt Chromium Y Standard Archwires

after Heat Treatment at 482°0 C for 12 minutes

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ϕ Total Deflection.