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ELASTIC PROPERTIES OF ORTHODONTIC WIRE

A project report
submitted in partial fulfilment for the degree of
Master of Dental Surgery
by

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SUMMARY

The selection of wires for use in orthodontic appliances is often an empirical procedure based upon clinical impressions. The results of the mechanical tests used to examine orthodontic wires do not necessarily predict the behaviour of the wires in clinical use. Therefore, this study was undertaken to evaluate the customary tests for orthodontic wires, investigate alternative methods of examination and test wires currently available for use as archwires in the Begg orthodontic appliance. Eight wires were examined; namely, Wilcock Premium Plus, Premium, Special Plus and Special grades, Unitek Unisil, Dentaurum Remanit Super Special Spring Hard and Yellow and Green Elgiloy from The Rocky Mountain Dental Products Company.

From an examination of the relevant literature it was concluded that the elastic properties of wires were most relevant in predicting desirable clinical behaviour. The tensile mechanical properties of proportional limit, proof stress, ultimate tensile strength and Young's modulus of elasticity of each wire were determined as measures of elastic properties.

The results of this investigation showed that the proportional limit is the only satisfactory measure of elastic properties. However, the 0.1% proof stress value may be used to quantitatively compare wires with similar strain-hardening rates. The ultimate tensile strength may only be used to qualitatively grade wires with respect to their elastic properties while Young's modulus of elasticity is only of marginal value in comparing orthodontic wires.

Of the wires tested, Wilcock Premium Plus and Premium had the best elastic properties. There were no significant differences between the other wires.

The stress relaxation characteristics of the wires were investigated to determine the importance of this phenomenon on archwire performance. Stress relaxation occurred in all wires and over a three day period Wilcock Premium Plus, Premium and Special Plus wires exhibited superior stress relaxation properties when compared with the other wires.

The hardness of all wires was measured and it was found that this parameter may also be used to qualitatively grade wires.

The microstructure of the wires was examined using metallographic techniques involving simple chemical etching procedures. However, these procedures were not suitable for revealing the fine structures of orthodontic wires.

This investigation has demonstrated that Wilcock Premium Plus and Premium have the best elastic properties of the wires currently available for use in the Begg orthodontic appliance. Conventional testing did not demonstrate any significant differences between the other wires although the results of the stress relaxation tests suggested that Wilcock Special Plus may be superior.

SIGNED STATEMENT

This project report is submitted in partial fulfilment of the requirements of the Degree of Master of Dental Surgery in The University of Adelaide.

This report contains no material which has been accepted for the award of any other degree or diploma in any University. To the best of my knowledge and belief, it contains no material previously published or written by another person except when due reference is made in the text of the report.

COLIN C. TWELFTREE.

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1. INTRODUCTION

1.1 General

The archwire is an important component of an orthodontic appliance. There is commercially available a range of wires purportively suitable for archwire construction. An orthodontist is required to select the best wire available for use in his appliance. To rely upon clinical judgement and impressions is not sufficient. Ideally, one should be able to critically read the relevant specifications of a wire to judge its suitability as an archwire in an orthodontic appliance. These specifications should include those mechanical properties which will predict the behaviour of the wire in clinical use.

The choice of suitable tests has been the subject of much discussion in the literature but there is not universal agreement regarding which properties are the most important. It is generally agreed that tests which measure the elastic behaviour of wires are most relevant. However, elasticity can be described by many different mechanical properties and measured by different methods.

It is necessary to resolve this dilemma to enable improved evaluation of the wires currently available and to establish sound guidelines for future development of orthodontic wires.

1.2 Scope of the Present Work

This investigation is concerned with an examination of those wires which are commonly used or have been suggested as being suitable for construction of a Stage I archwire in the Begg orthodontic appliance. Consequently, only wires of 0.016 inch (0.4 mm) diameter will be tested (BEGG AND KESLING, 1971).

Emphasis will be directed towards comparative testing of the wires for those properties which are generally considered to specifically determine the effectiveness of an archwire in clinical use. Other properties which may relate information regarding these qualities will also be investigated.

In addition, metallographic techniques will be used in an attempt to correlate the structure of the wires with their properties, thereby providing information for the development of superior wires.

2. MECHANICAL PROPERTIES OF MATERIALS

This chapter outlines the various properties of materials which will be used to describe the performance of orthodontic wires. The major reference work is 'Nature and Properties of Engineering Materials' by JASTRZEBSKI (1959).

Mechanical properties determine the behaviour of materials under applied forces and loads. The response of solid materials to applied forces depends on the type of bonding and the structural arrangement of atoms or molecules. The arrangement may be greatly modified by manufacturing processes and treatments, thereby resulting in a broad range of properties even in materials of the same chemical composition.

There are three basic types of deformation that are involved in the response of all materials to applied forces. These are elastic, plastic, and viscous deformation. Materials can be classified according to their mode of deformation. Metals in general, and metallic orthodontic wire in particular, are classified as elastoplastic materials because they mainly deform in either an elastic or a plastic manner.

An isotropic material has the same properties in all directions. No material is perfectly isotropic but many approach this condition and are considered to behave in this manner. Anisotropy of polycrystalline materials may result from plastic deformation and marked reorientation of the individual grains. Under these circumstances, the stresses and strains resulting from load on the material will largely depend on the relationship between the direction of the force and the orientation of the grains. Therefore, the properties of the material will be very directional. Orthodontic wire, which has been heavily worked in the drawing processes, shows very definite preferred orientation of the grains of the metal, and so must be considered as an anisotropic material.

2.1 Elasticity

Any force or load applied to a body will result in stress and strain in the material. Stress represents the intensity of the reaction force to the load at any point in the body. It is measured as the force acting on unit area of a plane.

$$\text{i.e.} \quad \text{stress} = \frac{\text{force}}{\text{area}} \qquad \text{or} \quad \sigma = \frac{F}{A}$$

This was usually expressed in pounds per square inch (p.s.i.). With the universal adoption of Systѐme Internationale units, stress is now usually expressed in newtons/square meter (N/m^2) or Pascals (Pa).

Forces or loads acting on the body may be static or dynamic. Static forces remain essentially constant or change slowly without exhibiting any repetitive characteristics. Dynamic forces can be impact forces, alternating forces and reverse forces. Impact forces are produced when the kinetic energy of colliding bodies is absorbed by deflection in the material; e.g. masticatory forces on an archwire. Alternating forces fluctuate between two limits, usually in a sinusoidal manner as during vibration. Reverse forces are essentially alternating forces having two limits, equal in magnitude but opposite in sign.

A stress is compressive if it tends to bring the material into closer contact; it is tensile if it tends to separate the material. When the forces are parallel to an imaginary plane at a point, shear stress results.

The alteration in the shape or dimensions of a body resulting from stress is called strain or deformation. Strain is expressed in dimensionless units such as mm per mm or as a percentage. Since there are three main types of stress, strains of tensile, compressive and shear character can be distinguished.

Tensile strain is expressed as elongation per unit length (Fig. 1).

Compressive strain is measured by the ratio of the contraction to the original length (Fig. 1).

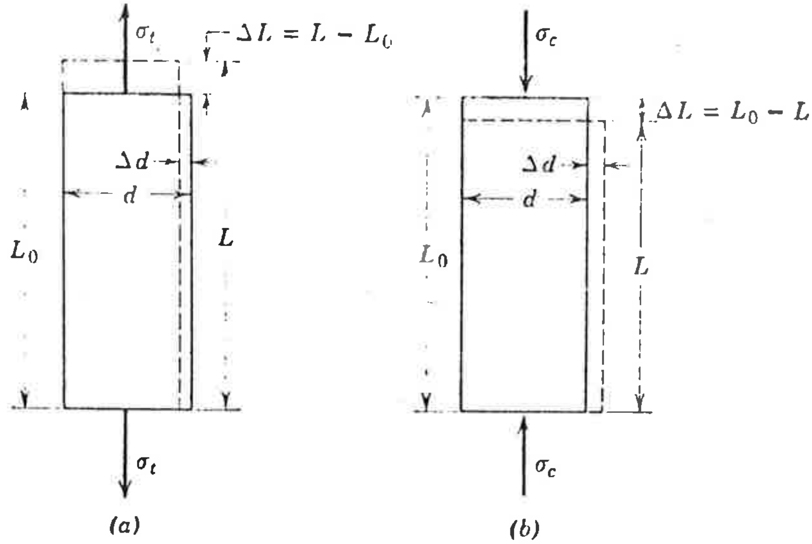
Shear strain is measured from the magnitude of the angle resulting from the change in inclination of a certain plane subjected to a pure shear stress and a line perpendicular to this plane (Fig. 1).

A material responds to a force in an elastic manner when the total strain produced in the body is immediately recovered after removal of the applied stress. Hooke's Law, which states that stress is proportional to strain describes the relationship between the elastic stress and strain in a material.

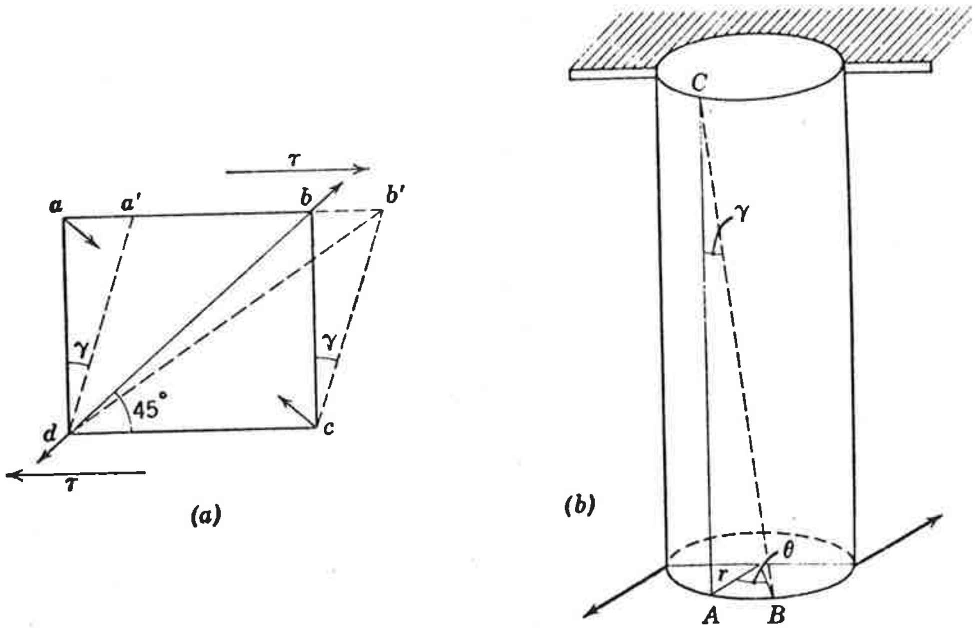
In an isotropic material, each stress will induce corresponding strain, but for an anisotropic material, a single stress component may produce more than one type of strain in the material.

2.1.1 Modulus of Elasticity

The ratio between stress and strain is a constant characteristic of a material and is called the modulus of elasticity. Since there are three main types of stress, tensile, compressive and shear, there are three corresponding moduli of elasticity.



Tensile and compressive strain. (a) Tensile strain or longitudinal strain $\Delta L/L_0 = (L - L_0)/L_0$ with corresponding lateral strain $\Delta d/d$. (b) Compressive strain $\Delta L/L_0 = (L_0 - L)/L_0$.



(a) Shear strain $\gamma = aa'/ad$ equivalent to longitudinal elongation along *db* and contraction along *ac*. (b) Shear strain $\gamma = \theta r/L$ in torsion.

Fig.1 (JASTRZEBSKI, 1959)

1. The modulus of elasticity in tension, or Young's Modulus, denoted as E, $= \frac{\text{tensile stress}}{\text{tensile strain}}$ i.e. $E = \frac{\sigma_t}{\varepsilon_t}$

2. The modulus of compressibility, K, $= \frac{\text{stress}}{\text{volumetric strain}}$

3. The shear modulus, G, $= \frac{\text{shear stress}}{\text{shear strain}}$

Isotropic materials require only these three constants to uniquely define their elastic properties whereas highly anisotropic materials may require as many as nine elastic constants to describe the directionality of response. However, for an anisotropic material it is usually sufficient to measure only the properties in the direction in which the material will be used in practice.

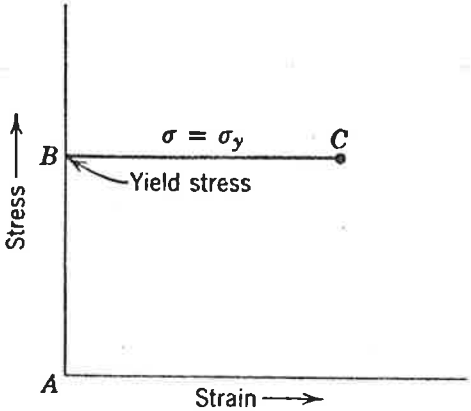
2.2 Plasticity

When a material responds elastically to a load, there is complete recovery when the load is removed. There is no permanent displacement of the atoms or molecules. In practice, this only applies to very small deformations. When a certain stress is exceeded, many materials show a permanent non-recoverable deformation. This is called plastic deformation and is the result of permanent displacement of atoms or molecules or groups of atoms and molecules from their original positions in the lattice. The displaced atoms and molecules do not return to their original positions after the removal of stress. If a material subjected to a constant load of a sufficient magnitude shows a continuously increasing deformation, the phenomenon is called flow.

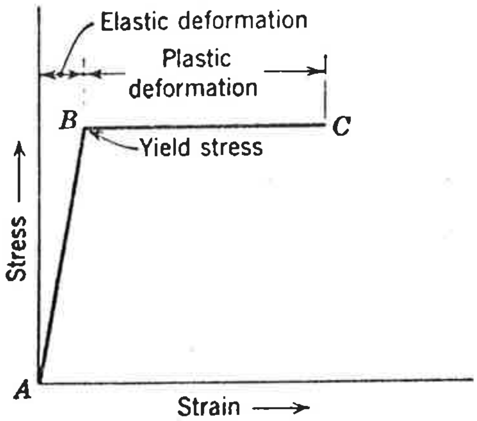
Ideal plasticity occurs when deformation proceeds continuously at a constant stress equal to the yield stress (Fig. 2). For most materials elastic deformation precedes the plastic strain, producing the curve shown in Fig. 2. Hooke's Law is obeyed for stresses below the yield stress and this is followed by ideal plastic deformation. Such materials are called elastoplastic bodies. In practice, most materials do not exhibit ideal elastic or plastic strain and their stress-strain curve is shown in Fig. 2 where there is a slightly curved line in the latter portion of the elastic range and a considerable increase in strain in the plastic range. The slope of the curve during plastic deformation is termed the strain-hardening rate.

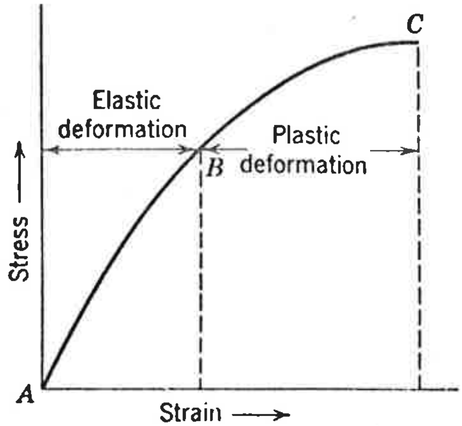
2.2.1 Mechanism of Plastic Deformation

In crystalline materials, of which orthodontic wire is an



Ideal plastic body (St. Venant's solid).



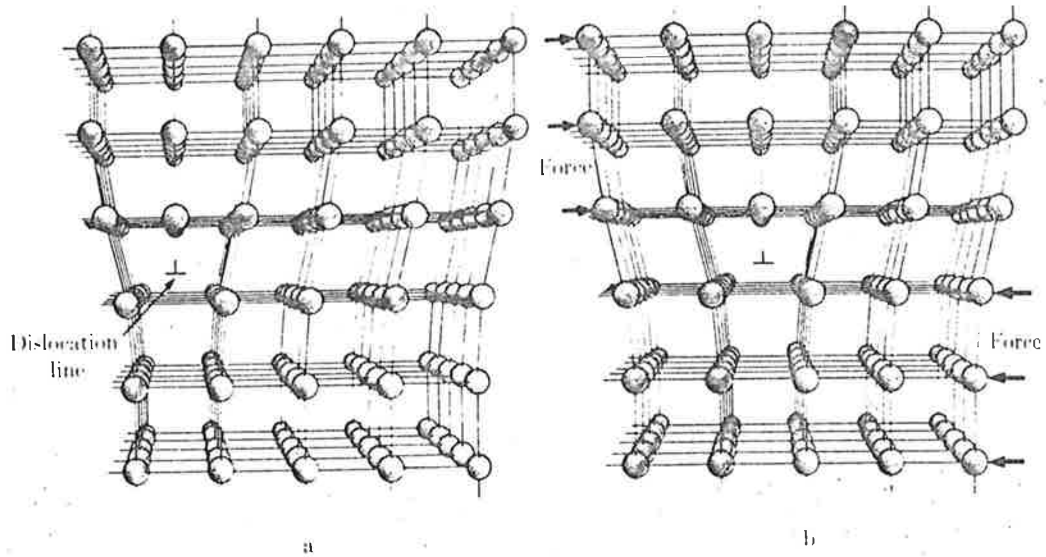


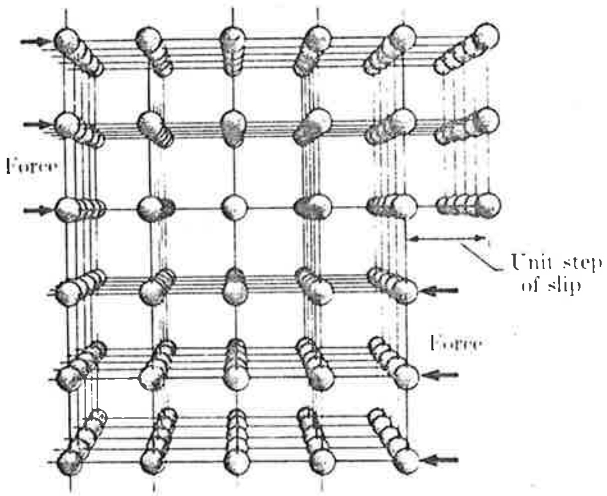
Ideal plastic deformation preceded by ideal elastic deformation.
Elastic and plastic deformation of rigid bodies.

Fig.2 (JASTRZEBSKI, 1959)

example, plastic deformation usually occurs by slip or shear along definite crystallographic planes (SKINNER and PHILLIPS, 1967). In a structure with a perfect space lattice, the stress required to cause this slip can be calculated. However, the observed yield stress required for slip in real metal crystals is much lower than the theoretical stress because every crystal contains imperfections from which slip can start at a lower stress. During solidification of the metal, the growth is likely to be irregular in places and this introduces defects such as vacancies and dislocations in the crystal lattice.

The main difference between an ideal lattice and the structure of real metals is the presence of dislocations in the latter. Dislocations are essentially linear disturbances of the atomic arrangement which can move very easily on the slip plane through the crystal. Plastic deformation is mainly due to movement of dislocations. The simplest type of dislocation is known as an "edge dislocation" and is illustrated diagrammatically in Fig. 3. The lattice is regular except for the one plane of atoms which is discontinuous and forms a dislocation line. If a shearing force is applied to the crystal, the atoms in the plane above the dislocation easily establish new bonds with the lower atoms. The dislocation is easily moved through the lattice until it either emerges at the free surface of the crystal or meets some type of lattice discontinuity which may inhibit its gliding motion. Such discontinuities may be (1) point defects, (2) immobile dislocations caused by dislocation interactions, (3) a foreign atom or precipitate particle or (4) a grain boundary. In polycrystalline metal, the dis-





An edge dislocation in a crystal space lattice (*a*). In *b* the dislocation has moved one lattice spacing under the action of the shearing force or load as indicated by the arrows. In *c* the dislocation has reached the edge of the crystal and a unit slip has been produced. (From Guy. *Elements of Physical Metallurgy*. Addison-Wesley Publishing Co., Inc.)

Fig.3

locations tend to pile up at the grain boundaries. The barrier action to slip at the grain boundaries also causes the slip to occur on other intersecting slip planes. The dislocation density increases and the entire grain may eventually become distorted. A greater stress is required to produce further slip and the metal becomes stronger and harder. This process is known as strain hardening or work hardening.

Plastic deformation is of great importance in the fabrication of metals. When fabrication is carried out at temperatures below the recrystallization temperature, the process is called cold work. Because of the strain-hardening effect, there is a considerable increase in the hardness, yield point and strength after cold work. These changes are accompanied by a marked decrease in ductility.

Part of the work done on a metal during plastic deformation is stored as internal energy. From a thermodynamic viewpoint there is a tendency for the material to return to a lower energy state by atomic diffusion processes. The rate of diffusion for most metals is very low at room temperature but with the application of heat, recovery or recrystallization may occur.

2.2.2 Recovery

Recovery takes place at relatively low temperatures. The internal stresses are relieved with little effect on the properties achieved by the cold working. This process is also called stress relieving.

2.2.3 Recrystallization

Recrystallization occurs when the rate of atomic diffusion is increased to such an extent by the increase in temperature that a new grain structure replaces the old structure. The lowest temperature at which this process occurs is the recrystallization temperature. The new grains that are formed are equiaxed and stress free. Consequently, this process removes the effects of cold work.

The amount of recrystallization that occurs is dependent on temperature, time, and the degree of previous cold work. The size of the grains formed is dependent on the temperature and the size of the grains in the cold worked condition. If recrystallization is allowed to proceed, growth of the larger recrystallized grains occurs at the expense of the smaller ones. This further destroys the strength but increases the ductility of the metal.

2.2.4 Hot Working

When plastic deformation of a metal is carried out at temperatures above the recrystallization temperature, there are no appreciable changes in mechanical properties. This process is known as hot working and any strain hardening caused by the deformation is immediately recovered by the effect of the high temperature. During hot working the density of the metal is increased, the grain structure becomes refined, and an improvement in the homogeneity of the material is obtained.

2.2.5 Viscosity

Viscosity is the property which determines the flow of a material. It may be equated with the amount of internal friction resisting the flow of the material. For ideal, or Newtonian viscosity, the shear stress is proportional to the rate of application of shear strain. The proportionality constant is the coefficient of viscosity (η)

$$\text{Thus} \quad \sigma = \eta \frac{d\varepsilon_v}{dt}$$

where σ = stress

$\frac{d\varepsilon_v}{dt}$ = strain rate

2.2.6 Viscoelasticity

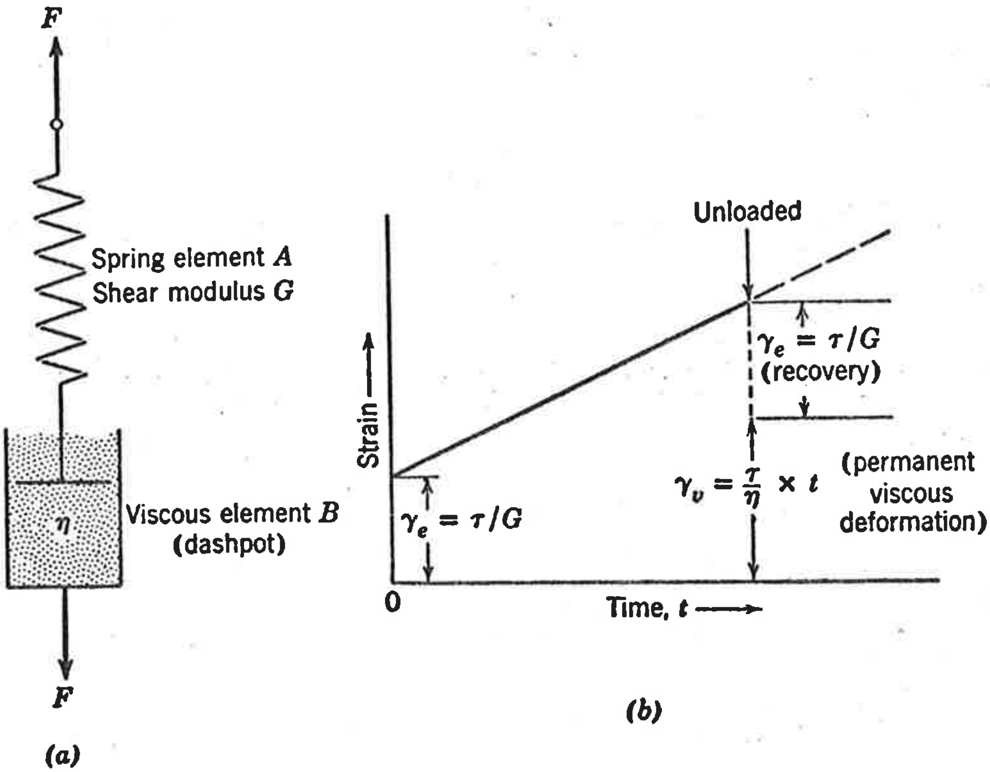
Viscoelastic deformation occurs when a material responds to an applied force by exhibiting both elastic and viscous deformation. This type of behaviour is usually represented by a mechanical analogue containing a spring (elastic behaviour) and a dashpot (ideal Newtonian viscosity). A dashpot is a plunger in a cylinder filled with fluid. Movement of the plunger is governed by the viscosity of the fluid.

One analogue frequently used to represent viscoelastic behaviour is the Maxwell Model which consists of a spring and a dashpot in series (Fig. 4).

When a load, F, is applied to this model, there is an instantaneous elastic response from the spring. The amount of elastic strain is proportional to the shear modulus (G) of the spring (Fig. 4). The dashpot also begins to deform at a rate inversely proportional to the coefficient of viscosity i.e. $\frac{\gamma}{\eta}$ where

γ = stress

η = coefficient of viscosity.



Deformation for a relaxing material: (*a*) Maxwell element; (*b*) strain-time diagram for a Maxwell body. The material deforms continuously under constant stress. On unloading, only elastic deformation is recovered.

Fig.4 (JASTRZEBSKI, 1959)

Therefore, if the stress remains constant, the total strain is equal to the sum of the elastic and viscous strains and constantly increases as the viscous strain increases.

2.2.7 Creep

Creep can be defined as the slow and progressive deformation of a material under a constant applied stress. It is caused by the response of the viscous element in the material to the applied load. The rate of creep in metals is affected by many conditions, e.g. grain size, microstructure, test temperature and previous strain history.

Generally coarse grained materials exhibit better creep resistance than fine grained ones. Fine grained metals have a greater grain-boundary area which behaves as a "quasi-viscous" solid with a high tendency to flow at elevated temperatures. However, the creep ductility of coarse grained material is usually quite low (FLECK, COCKS and TAPLIN, 1970).

2.2.8 Stress Relaxation

If a stressed material is held at constant strain, stress relaxation may occur in the manner predicted by the Maxwell Model held at constant strain. The amount of stress decay depends on the characteristics of the viscous element of the material. Although metals are essentially elastoplastic materials (JASTRZEBSKI, 1959) grain boundaries may behave as a viscous element and thereby permit stress relaxation.

The relaxation time (t_r) of a material is defined as the time required for the stress to decay to $\frac{1}{e}$ of its original value. 'e' is a mathematical constant equal to 2.7183.

2.2.9 Fracture of Materials

Fracture denotes complete destruction of the cohesion of the material, resulting in the separation of a portion of the material body. There are many different mechanisms that may lead to fracture which is, as yet, very little understood. It is described in terms of the deformation that preceded it (brittle or ductile fracture), the appearance of the fracture (fibrous or granular), or its crystallographic nature (shear or cleavage).

The occurrence of brittle or ductile fracture depends on the values of the shear strength and cohesive strength of the material. If the shear strength is greater than the cohesive strength, the material will fail in a brittle manner; but if the shear strength is less than the cohesive strength, the material will be ductile and deform plastically before it fractures.

Another important factor in determining brittle or ductile type of failure of a material is the distribution of stresses. For example, biaxial and triaxial stresses occurring at notches make a normally ductile metal brittle under impact stresses.

2.3 Properties Related to Strength

Strength is the ability of a material to resist applied forces without yielding or fracturing. Strength data are usually obtained from laboratory determinations of stress-strain curves. Other properties such as ductility, stiffness, resilience and toughness can be estimated from this data. The tests can be carried out under tension, compression, bending and shear either under static or dynamic loads.

The static tension test is normally used for orthodontic wire (SKINNER and PHILLIPS, 1967). A static test is one in which the speed of application of the load has a practically negligible effect on the shape of the stress strain curve. In this test, the specimen is gradually loaded along its long axis. The load is plotted against the extension, as described in Section 5.2.1. The results are usually restated in terms of stress and strain which are independent of the geometry of the sample (DAVIS, TROXELL and WISKOCIL, 1964).

The engineering stress, σ, is equal to the ratio of the load on the sample, P, to the original cross-sectional area, A_o (DIETER, 1961).

$$\text{i.e.} \quad \sigma = \frac{P}{A_o}$$

The engineering strain, ε, is defined as the ratio of the change in length of the sample, to its original length, L_o.

$$\text{i.e.} \quad \varepsilon = \frac{\Delta L}{L_o}$$

The graph obtained from a specimen of orthodontic wire has the general shape shown in Fig. 5. The first part of the curve is

Stress-strain curve for a stainless steel orthodontic wire under tension. Proportional limit, 167,000 pounds per square inch; modulus of elasticity, 33,300,000 pounds per square inch; modulus of resilience, 420 inch-pounds per cubic inch; ultimate tensile strength, 235,000 pounds per square inch.

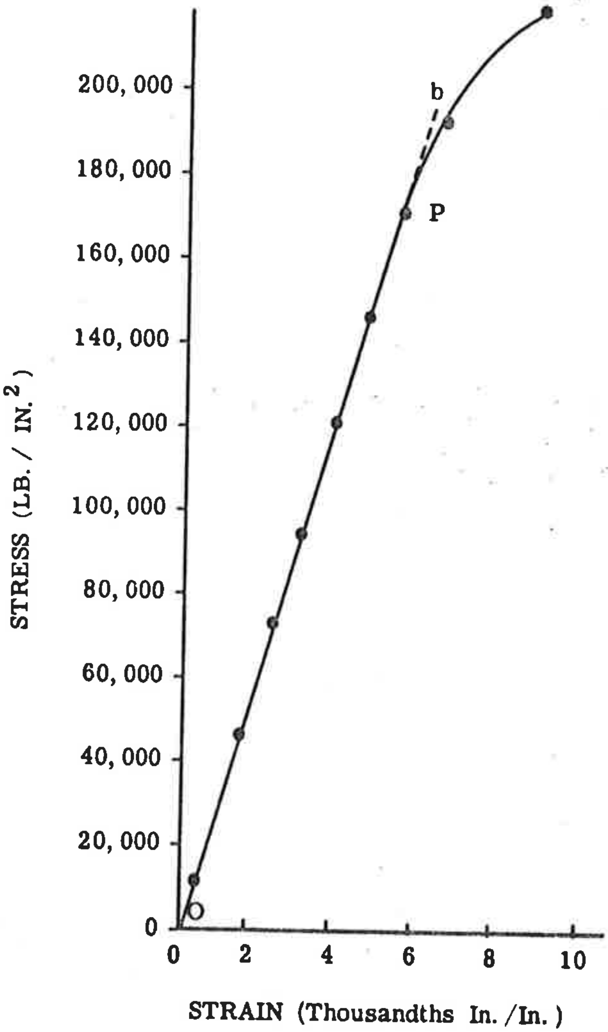


Fig.5 (SKINNER and PHILLIPS, 1967)

essentially a straight line. In this area, stress is proportional to strain and the material behaves elastically. If the load were removed during this range, the strain would completely recover.

2.3.1 Proportional Limit

The value of stress where direct proportionality between stress and strain ceases is known as the proportional limit (P) of the specimen (SKINNER and PHILLIPS, 1967).

The slope of this initial straight-line portion of the curve is a measure of the stiffness of the material. The ratio of stress to strain in this area is the modulus of elasticity in tension, or Young's Modulus, E. $\sigma = E\varepsilon$.

2.3.2 Elastic Limit

The elastic limit is the greatest stress a material is capable of withstanding without producing a permanent deformation upon release of that stress. Tensile tests do not give the value of the elastic limit which can only be determined by successive loading and unloading of the specimen. For ductile materials, the elastic limit is very close to the proportional limit.

2.3.3 Yield Point

Ductile materials may also exhibit a yield point. The yield stress is defined as the lowest stress at which an increase in strain occurs without any increase in stress.

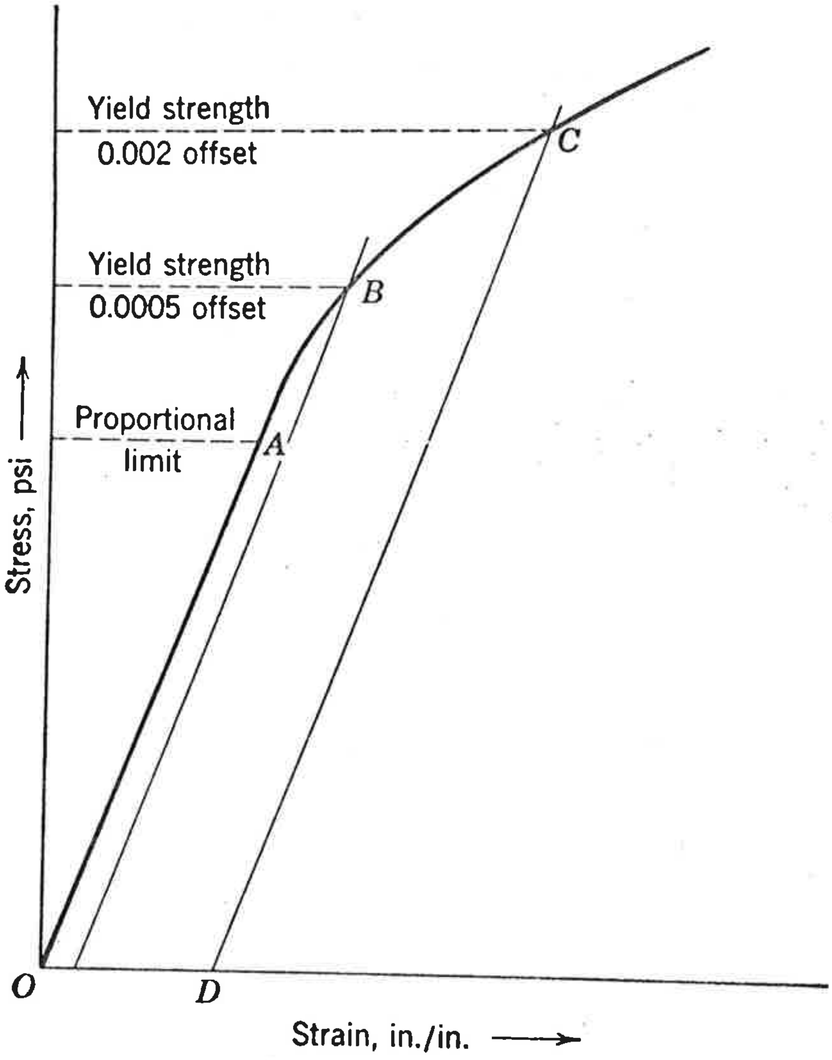
2.3.4 Ultimate Tensile Strength

As the specimen under tension is strained beyond its yield point, the stress increases to a maximum termed the ultimate tensile strength. After further strain, fracture occurs at the "breaking strength". The deformation of the wire past the yield point involves plastic strain. On release of the load there will be permanent deformation in the sample.

Orthodontic wire is not a ductile material and the stress-strain curve does not show a marked change of slope in the area where plastic deformation begins. No definite yield point can be determined and there is difficulty in determining the stress when plastic deformation begins. As the measuring devices become more sensitive, the elastic limit is decreased. For most metals there is only a rather narrow range over which Hooke's Law strictly applies (DIETER, 1961).

2.3.5 Proof Stress

To provide a definite stress that can be measured on different testing instruments the property of proof stress is used. The proof stress of a material is the stress required to produce a certain permanent strain. This is determined by the "offset" method (Fig. 6). Starting with a certain strain, a line (DC) parallel to the straight line portion of the curve (OA) is drawn to its intersection with the curve. The stress corresponding to this point is called the proof stress. The strain at which the proof stress is measured depends on the material. MASSON (1969) used 0.02 percent strain to determine the proof stress of orthodontic wire.



Proof stress determination.

Fig.6 (JASTRZEBSKI, 1959)

2.3.6 True Stress-Strain Curve

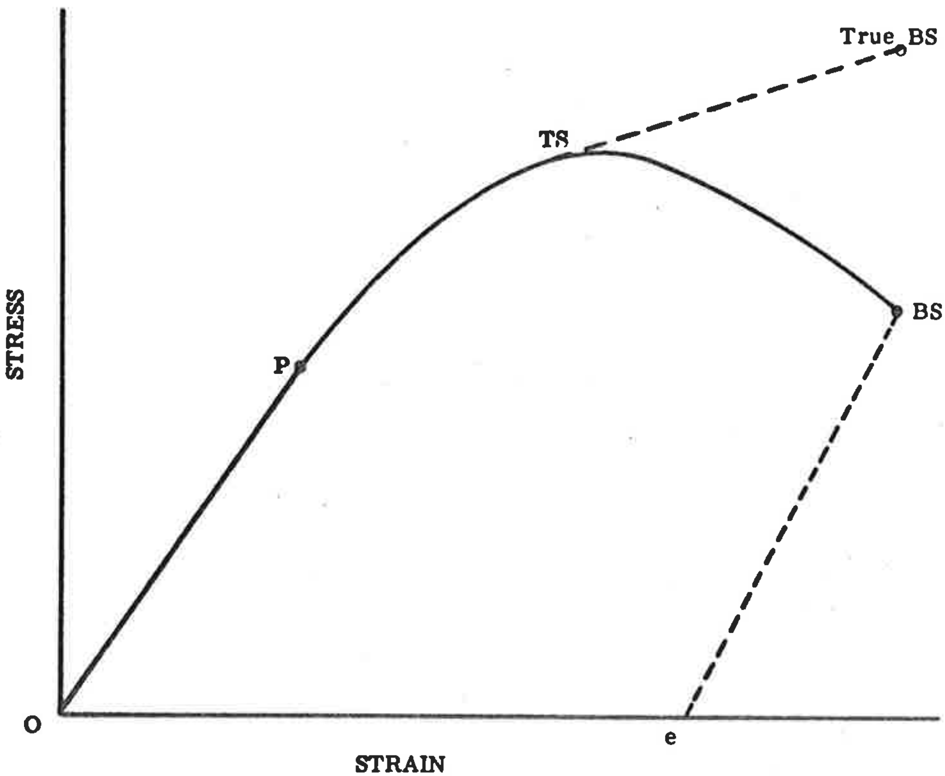
The stress-strain curve of a ductile material indicates that the fracture stress is less than the ultimate tensile stress. This is because the stress has been calculated on the assumption that the area of cross-section has remained constant. If the reduction in area is considered, the true stress at fracture is the maximum stress (Fig. 7). This is important when ductile materials are being considered. However, as ductility decreases to the ductility level of hard drawn orthodontic wires, this phenomenon can, for practical purposes, be ignored.

2.3.7 Ductility

Ductility is the ability of a material to deform plastically without fracture. The best predictions of the ductility of a material for a particular situation are tests which duplicate the strains found in actual usage (DIETER, 1961). An estimate of ductility can be predicted from the tensile test using the percentage elongation to fracture. For ductile materials the reduction in area to fracture may also be used. The most common test for orthodontic wires at present is the cold bend test in which a sample is bent through a pre-set angle. The number of cycles achieved before fracture is used as a measure of ductility (DOCKING, 1965).

2.3.8 Resilience

Resilience is the ability of a material to absorb energy during elastic deformation. The modulus of resilience is measured by the area under the elastic portion of the stress-strain curve. It is determined



Solid line—complete stress-strain curve as determined by ordinary testing methods: P, proportional limit; TS, tensile strength; BS, breaking strength. If stress were computed according to the actual diameter of the wire, the dotted line portion of the curve would result, with the "true" breaking strength as shown.

Fig.7 (SKINNER and PHILLIPS, 1967)

mathematically by dividing the square of the proportional limit by twice the modulus of elasticity. The proof of this is as follows (SKINNER and PHILLIPS, 1967). Let R = modulus of resilience.

P = proportional limit.

ε = maximum flexibility i.e. strain at proportional limit.

E = modulus of elasticity.

Since the structure is stressed continuously from zero to P, the average force $= \frac{0 + P}{2} = \frac{P}{2}$.

Then the total work done per unit volume =

$$R = \frac{P}{2} \times \varepsilon$$

$$= \frac{P}{2} \times \frac{P}{E} \quad (\text{as } E = \frac{P}{\varepsilon})$$

$$= \frac{P^2}{2E}$$

The units for the modulus of resilience are expressed as energy per unit volume.

2.3.9 Toughness

Toughness is the ability of a material to absorb energy during plastic deformation. In the static tensile test it is measured as the area under the stress-strain curve to fracture. The specific property is the modulus of toughness, which is the maximum amount of energy a unit volume of the material can absorb without fracture. Toughness is desirable in parts subjected to dynamic loads such as shock or impact. It is often determined from an impact test in which a predetermined load is suddenly applied to a specimen.

2.3.10 Hardness

The hardness of a material is usually measured as the resistance to indentation. Its value depends on several fundamental properties including yield and tensile strengths, ductility, work hardening characteristics and resistance to abrasion.

The method of measuring hardness determines the relative importance of these properties. Correlations have been established between hardness and proportional limit (SKINNER and PHILLIPS, 1967) and ultimate tensile strength (BUSH, TAYLOR and PEYTON, 1951; WILKINSON, 1960, 1962) of stainless steels used in dentistry.

The hardness of a material may be altered by many processes including alloying, cold work and precipitation hardening.

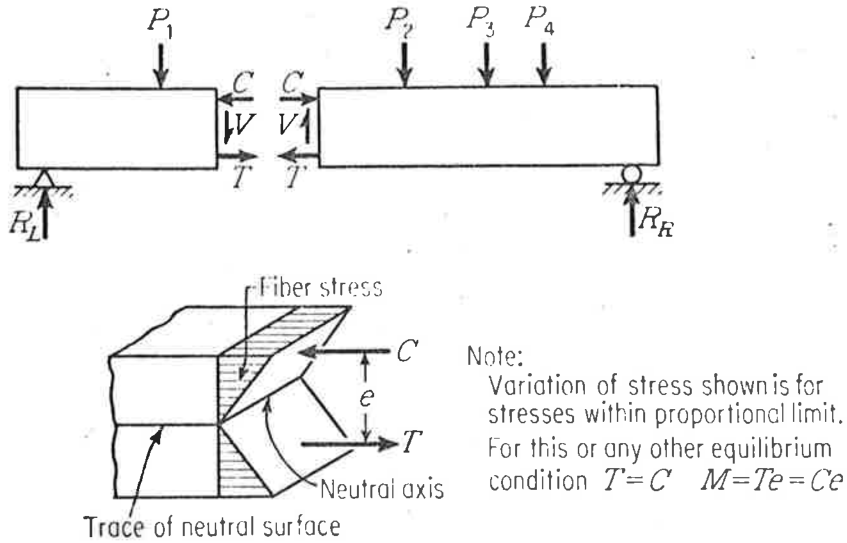
2.4 Behaviour of Materials Subjected to Bending

If forces act on a piece of material in such a way that they tend to induce compressive stresses over one portion of a cross-section and tensile stresses over the remaining part, the piece is said to be in bending (DAVIS, TROXELL and WISKOCIL, 1964).

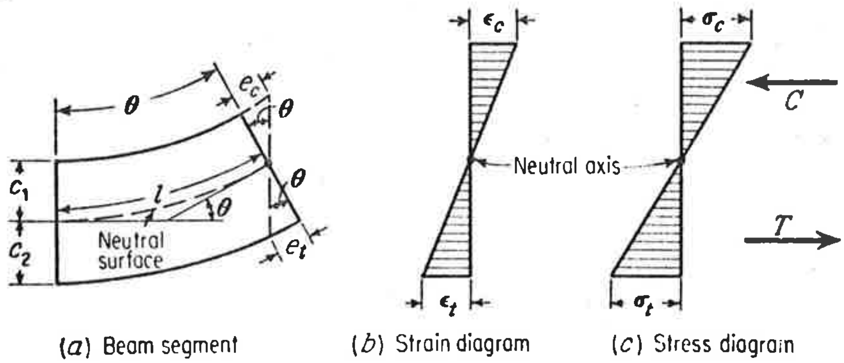
The customary illustration of a bending action is a beam acted upon by transverse loads.

When a beam is subjected to transverse loading, the bending effect at any section is expressed as the 'bending moment' which is the sum of the moments of all forces acting to the left (or to the right) of the section (Fig. 8). The stresses induced by a bending moment may be termed bending stresses. For equilibrium, the resultant of the tensile forces must equal the resultant of the compressive forces. The resultants of the bending stresses at any section form a couple that is equal in magnitude to the bending moment (Fig. 8). When no stresses act other than bending stresses, a condition of 'pure bending' is said to exist. Bending is usually accompanied by transverse shear and torsional shear. In a cross-section of a beam, the line along which the bending stresses are zero is called the neutral axis. On the compressive side of the beam the fibres shorten and on the tensile side they stretch. Thus the beam bends or deflects.

In pure bending, the strains are proportional to the distance from the neutral axis. If stresses are proportional to strains (that is, within the proportional limit) the stress variation across a section is linear.



Bending of a beam.



Fiber strains and stress due to bending within the proportional limit.

Fig.8 (DAVIS, TROXELL and WISKOCIL, 1964)

The deflection of a beam is the displacement of a point on the neutral axis from its original position. Within the proportional limit, the deflection may be computed from the modulus of elasticity of the material and the properties of the section. The deflection of different types of beams is summarized in Fig. 9.

The value of the modulus of elasticity in flexure may differ from the modulus of elasticity in tension. This difference may occur because the moduli in tension and compression are different, in which case the modulus in flexure will lie between the tension and compression values. If there are transverse shearing stresses, the modulus in flexure tends to be lower than the modulus in tension.

Above the proportional limit, bending stresses do not vary linearly across a section because stress is not proportional to strain. If the material does not have the same stress-strain characteristics in tension as in compression, the neutral axis must shift toward the stiffer side of the beam in order to maintain equality of the tensile and compressive forces.

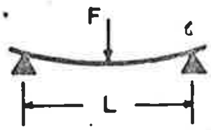
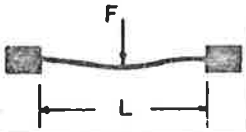
Type of Beam	CANTILEVER	FREELY SUPPORTED	RIGIDLY SUPPORTED
Form of Beam			
Deflection D	$\frac{1}{3} \cdot \frac{L^3 F}{E I}$	$\frac{1}{48} \cdot \frac{L^3 F}{E I}$	$\frac{1}{192} \cdot \frac{L^3 F}{E I}$
Ratio of deflection for the same force	64	4	1
Deflection for round wires $I = \frac{\pi d^4}{64}$	$\frac{64}{3\pi} \cdot \frac{L^3 F}{E d^4}$	$\frac{4}{3\pi} \cdot \frac{L^3 F}{E d^4}$	$\frac{1}{3\pi} \cdot \frac{L^3 F}{E d^4}$
Deflection for rectangular wires $I = \frac{W T^3}{12}$	$\frac{64}{16} \cdot \frac{L^3 F}{E W T^3}$	$\frac{4}{16} \cdot \frac{L^3 F}{E W T^3}$	$\frac{1}{16} \cdot \frac{L^3 F}{E W T^3}$

Fig.9 (WARE, 1967)

3. LITERATURE REVIEW

3.1 Development of Orthodontic Archwire Materials

A variety of materials have and are being used for orthodontic archwires. The changes that have been made are due mainly to differing functions of archwires and the development of new materials. In the eighteenth century the precious metals gold and silver, or alloys of these, were used as prototype archwire forms. However, these were rigid appliances of ideal dental arch form toward which the teeth were gradually drawn by the tightening of ligatures (WEINBERGER, 1926).

The concept of the active archwire was later developed, (ROBINSON, 1918; ATKINSON, 1937; JOHNSON, 1938; BEGG, 1954; and JARABAK, 1963) and the properties of the material became more important. Gold, gold and platinum, and iridioplatinum alloys were first used as active archwires. German silver, an alloy of copper, zinc and nickel, was popularised by Edward Angle in the early part of this century (RENFROE, 1960; DIXON, 1972). The development of stainless steel in the third decade of this century (GASTON, 1951) signified the beginning of a new era in orthodontic materials (ADAMS, 1958). This material had the advantages of resistance to corrosion and superior strength, especially in small diameters (CARMAN, 1938). By comparison, stainless steel wires are generally twice as stiff as gold (THUROW, 1962).

Over two hundred varieties of stainless steel are available (RENFROE, 1960) but only a few are usable in the mouth. The most common stainless steel used is of the 300 series (austenitic) and is referred to as 18-8 stabilized steel or chrome steel. The term 18-8 refers to the respective percentages of chromium and nickel in the alloy. This series of stainless steel is not hardened appreciably by any known heat treating method, although it is readily work hardened. Other steels that are used are the precipitation hardening types (CRAIG, SLESNICK and PEYTON, 1965). These steels may be hardened by both heat treatment and cold work.

Wrought nickel-chromium alloys are also used as orthodontic archwire materials (SKINNER and PHILLIPS, 1967). Their composition is 80% nickel and 20% chromium and they are commonly used as heating element wires. Their main advantage is a high recrystallization temperature. Thus, the danger of loss of mechanical strength from over-heating during soldering and similar heat treatments is minimised.

Elgiloy is an alloy recently developed by the Elgin Watch Company as a watch mainspring material (ROCKY MOUNTAIN GENERAL CATALOGUE, 1963). It is a cobalt-nickel spring alloy which is more corrosion resistant than stainless steel and can be spot welded, hard or soft soldered and hardened by heat treatment.

New alloys are constantly being developed and their suitability for use in orthodontics investigated (MOHAMMED and ASGAR, 1973).

3.2 The Begg Orthodontic Appliance

The Begg light wire appliance (BEGG, 1954; BEGG and KESLING, 1971) uses resilient round wires and light elastic forces to accomplish the required tooth movement. BEGG and KESLING (1971) stated that the technique could not have been developed if a suitable wire had not been produced.

The archwire is an active archwire in the true sense of the word. Incorporated into the arch form are certain characteristic bends which, as the wire is pinned to the teeth, become activated. Stresses are produced within the wire and as these tend to recover, forces are produced which act on the teeth. It is the extent and continued application of the sum of these forces which is vital for the efficient functioning of the appliance (MUNDAY, 1969).

Without doubt, the most important feature of the archwire is the anchorage bend (Fig. 10). When activated, the forces produced by this bend have two important functions. The first is to exert a depressing force on the anterior teeth to facilitate reduction of the overbite. This contributes to the free tipping of the anterior segments. The second function is to support the anchor molars in resisting the anterior component of forces exerted by the intermaxillary elastics. It is usually necessary to build expansion into the form of the archwire to provide lateral support for the anchor molars. This effect is achieved when the wire is inserted into the molar tubes and exerts a buccally directed force on these teeth.

The resiliency of the archwire is also used to align teeth

Fig.10 The Begg appliance showing the Anchorage Bends.

when the wire is elastically deformed by ligation to the bracket on a malposed tooth. As the archwire tends to recover its original shape, a force is exerted on the tooth. The flexibility of the archwire for this function may be increased by bending loops into the arch form. This effectively increases the range of activation of the wire.

For anchorage control and tooth alignment, it is necessary for the archwire to remain active for many months. Because the appliance is continuously subjected to masticatory forces the wire must be sufficiently resilient to resist permanent deformation and maintain its activation. Therefore, the elastic properties of the wire are of crucial importance for the efficient functioning of the appliance.

To shape the wire into the desired form, it is necessary to plastically deform it. The extreme example of this forming procedure is the bending of intermaxillary hooks or circles for the attachment of elastics. Bending hooks into the archwire does not affect the resiliency of the material, whereas the temperature level required to solder hooks to stainless steel may adversely affect the elastic properties of the wire (WILKINSON, 1962). Therefore, a degree of ductility is required to enable plastic deformation of the wire during the formation of the auxiliary bends.

3.3 Characteristics Required of an Orthodontic Archwire

In this section, references are cited which consider the general requirements of an archwire, without relating these requirements to specific physical properties.

BEGG (1954), in discussing the relative merits of stainless steel wires and platinised gold wires, stated that the main advantage of stainless steel wires was that they delivered a light gentle force over a long distance and when sprung, remained almost free from permanent distortion.

BURSTONE (1961, 1962, 1966, 1969) differentiated between active and reactive members of an orthodontic appliance. For the active members, which of course included the archwire, two main characteristics were important. A low load-deflection rate, i.e. force per unit activation, was most desirable, because the force remained more constant as the tooth moved and more accurate adjustments of the force magnitude were possible. The load-deflection rate was directly proportional to the elastic modulus of the material of the archwire.

The second important characteristic of an archwire material was the maximal elastic moment which was a measure of the force required to produce a permanent deformation. Besides allowing for a sufficient range of force application, this factor allowed a safety margin against overloading the archwire. Overloading could be produced during adjustment or from forces of mastication. This property was related to the elastic limit of the material.

THUROW (1962) claimed that stiffness was the first requirement that must be met in wire selection since it determined the relationship between force and deflection in the ideal working range.

NEWMAN (1963) referred to the need to compensate for the increased working stresses resulting from the selection of a wire of small diameter and increased length of span. Therefore, a wire with the maximum elastic properties should be selected.

In the ROCKY MOUNTAIN GENERAL CATALOGUE (1963) it was stated that orthodontists wanted a wire which would function longer as a resilient spring wire, without distortion or fatigue. Maximum properties were not necessarily best for all purposes, but small diameter wires required full spring properties.

MAHLER and GOODWIN (1967) reported that the mechanical properties of greatest significance in the clinical performance of small diameter wires were the elastic deformation/force ratio and the elastic force limit.

MUNDAY (1969) stated that the more resilient the wire, the more efficiently it would perform. Resiliency was a measure of the potential energy stored within the wire when elastically deformed into the bracket.

STONER (1969) claimed that the property of orthodontic wire of major concern was the range of deflection. This was the distance the wire could be deflected before it took a permanent deformation. Also of interest was the total load the wire could receive before a permanent deformation took place and the rate at which the load was reduced as the wire returned to its original contour.

The UNITEK LIGHT WIRE catalogue (1969) stated that for the Begg light wire technique, a wire was required with sufficient strength and resiliency to resist deformation from the forces of occlusion in the mouth.

STEPHENS and WATERS (1971) examined the reason why some high tensile stainless steel wires available for orthodontic use appeared to be clinically superior to others. They concluded that the ability of an unformed wire to resist permanent deformation was dependent on the amount of energy it could absorb elastically. They related this property to the stiffness of the wire and to the minimum radius to which the wire could be formed and yet return elastically to its original shape.

3.4 Physical Properties Required in an Archwire Material

References cited are those in which wires are tested or discussed with reference to specific physical properties which can be measured and recorded.

ANGELL (1950) compared gold alloy and stainless steel wire for orthodontic arches and springs. His basic unit of reference was the modulus of resilience. He also presented data on two wires which showed that these values varied depending on whether they were obtained from a tensile or bending test. He concluded that if tensile properties were used to establish the usefulness of materials, wrong conclusions would frequently be reached if the materials were to be used in bending. Therefore, for a wire to be used as a spring in transverse bending, the relevant characteristics should be determined by bending tests.

TAYLOR and PEYTON (1951) endeavoured to determine what correlation, if any, existed between the mechanical properties of wrought gold alloys as found in a standard tensile test and those found in a bend test. This was investigated because they noted that wires used in orthodontics were subject only to bend loading. Therefore, there was a feeling within the dental profession that the tensile test for wire was inappropriate and might be inferior to a bend test.

These workers measured the proportional limits and elastic moduli of twelve wires with greatly varying properties on a Tinius Olsen stiffness tester and a Tinius Olsen tensile testing machine. The proportional limits in bending (P_b) were plotted against the log of the tensile proportional limits (P_t). A straight line graph resulted which had an equation, determined by the method of least squares, of $\log P_t = 3.004 \times 10^6 P_b + 4.478$. This showed a definite correlation between the proportional limits obtained by the two methods.

Measurements of the moduli of elasticity were examined by the same method, but although certain trends were noted, no definite correlation could be obtained.

It was pointed out that in all physical testing to determine the properties of a material, some assumptions must be made. The assumptions for a tensile test (mainly that the area of cross-section remained constant) were few and introduced little error. However, for a bending test, the assumptions were more complex and introduced a larger deviation from the true properties of the material. The main assumptions in this case were that the material was truly elastic up to the proportional limit, the neutral axis did not shift and the material had identical properties in tension and compression. They concluded that as a basis for comparison of alloys, bend test data were as satisfactory as tensile test data.

BUSH, TAYLOR and PEYTON (1951) compared the mechanical properties, chemical compositions and microstructures of dental gold wires. They found that there was a definite correlation between hardness and tensile strength of wrought alloys of varying chemical composition and between the proportional limit and tensile strength of the wires. There was also a linear relationship between the Vickers hardness and the proportional limit in bending. Therefore, a linear relationship existed between the latter value and the ultimate tensile strength.

BACKOFEN and GALES (1951, 1952) determined the effects of heat treatment on stainless steel wires for orthodontics. They used the proportional limit and the modulus of elasticity as measures of the elastic properties of the material. They stated that an elastically stronger appliance was more likely to apply a larger force and return to its original shape without undergoing permanent deformation.

BRITISH STANDARD 2056 (1953). The main mechanical requirement of this standard for Rust, Acid and Heat Resisting Steel Wire for Springs related to tensile strength, the values for which varied with the diameter of the wire. A wrapping test, fracture test, dead wire test and a special bend test were also recommended.

KEMLER (1956) tested the effect of low temperature heat treatment on the physical properties of type 302 stainless steel wire and 80% nickel - 20% chromium wire. As an indication of the wire's suitability for use as an orthodontic archwire he measured the proportional limit, the modulus of elasticity and the modulus of resilience.

WILKINSON (1960) decided that the modulus of resilience governed a wire's suitability. For general use a wire should be strong enough to withstand the forces of mastication and yet springy enough to permit adaptation to misplaced teeth without producing a permanent set. As the modulus of elasticity was fairly constant, the proportional limit was the main governing limit. Only materials with a high modulus of elasticity could be produced with a high elastic limit. Clinically this could be compensated for by using wires of smaller diameter.

The relationships between hardness and tensile strength were also investigated by subjecting one wire to selected heat treatments. The results showed that the hardness of the wire was directly proportional to the tensile strength.

MUTCHLER (1961) tested the effects of heat treatment on the mechanical properties of cobalt-chromium wire and 18-8 chromium-nickel steel wire. He used the modulus of resilience as the basis for comparison. This parameter was related to the energy stored in a wire when stressed to its proportional limit and served to summarize the overall mechanical properties of the wire. The modulus of resilience was obtained from the proportional limit and the modulus of elasticity of the wire. These values were obtained by loading sections of the wire which had been cold worked by being formed into a loop. The resultant deformation of the loop was measured as the strain. The proportional limit and the modulus of elasticity were derived from the stress-strain curve.

BURSTONE (1961, 1962, 1966, 1969). In each of these references, it was stated that the mechanical properties of importance for an orthodontic alloy were the elastic limit and modulus of elasticity. The higher the elastic limit, the greater the load a wire could withstand without showing any permanent distortion. He considered that a safety factor should be incorporated against accidental overloading of the wire.

Burstone believed the elastic modulus should be as low as possible to produce minimal force per unit deflection. The lower this ratio, the more constant was the force acting as the teeth moved. An ideal spring would release a constant force throughout its range of activation. This ideal would be approached with a spring with a low load deflection rate and high allowable working loads.

WILKINSON (1962) discussed the metallurgical aspects of orthodontic stainless steel. He stated that as resilience was a measure of the ability to store energy, the proportional limit was the most important factor in determining the elastic properties of a wire. The proportional limits and tensile strengths of various wires were also measured and the ratio between these determined. The proportional limit, as a percentage of the ultimate tensile strength, varied from 36% to 59%. He therefore concluded that tensile strength could not be used as a reliable measure of proportional limit.

Experiments were also performed on a range of wires of similar chemical composition to determine the relationships between tensile strength and hardness. The following direct relationship was established:

Tensile Strength (p.s.i.)= 650 x Vickers
Hardness Number - 71,800 (p.s.i.)

DELGADO and ANDERSON (1963) compared the physical properties of hard and high tensile 18-8 stainless steel wires available in the British Isles. The relevant tests used were the tensile proportional limit, the ultimate tensile strength and a bend test. The proportional limits of the wires tested varied from 61-87% of the ultimate tensile strength. WILKINSON (1962) was cited, as was BILLBERG (1962), who suggested that for a high tensile wire, the proportional limit should be 90% of the ultimate tensile strength.

NEWMAN (1963) in his biomechanical analysis of the Begg light archwire technique stated that a wire with the highest proportional limit, yield strength and tensile strength should be selected to obtain maximum elastic properties. He also mentioned that the modulus of elasticity for stainless steel wires was fairly constant.

WILLIAMS (1964) tested the effects of residual stress, thermal stress-relief and electrolytic polishing on the proportional limit, modulus of elasticity and the modulus of resilience of "Australian Wire". The force applied in the test produced a bending type deformation of a sample of the wire bent through 90^0.

CRAIG, SLESNICK and PEYTON (1965) tested 17 - 7 precipitation - hardenable stainless steel wire to compare its suitability as an orthodontic archwire with 18-8 austenitic stainless steel and cobalt-chromium-nickel wires. The tensile properties tested included the yield strength, tensile strength and elastic modulus. Bend properties, resistance to breakage and micro-hardness were also tested.

DOCKING (1965), and WARE (1967) discussed the Australian Standard T32 for resilient orthodontic wire. The most important requirement was the tensile strength because it was related to the elastic limit and hardness of the wire. It also served to classify them according to the qualities expected in clinical practice. The other tests were for wrapping or coiling ability, resistance to failure on twisting and resistance to failure on bending. WARE documented the classifications of those wires which had been presented to the Commonwealth Bureau of Dental Standards. It was noted that Wilcock Special wire was classified Type C and Special Plus a Type D wire.

INGERSLEV (1966) examined the influence of heat treatment on the physical properties of bent orthodontic wire. He measured the elastic limit and the modulus of elasticity of the wire.

HOWE et al. (1968) tested the mechanical properties and stress relief of stainless steel orthodontic wire by determining the elastic modulus, yield strength and the ultimate tensile strength.

MASSON (1969) evaluated .016 stainless steel wires by determining the following properties:

Tensile tests	1.	Ultimate Tensile Strength
	2.	Proportional Limit
	3.	0.02% Proof Stress
	4.	Young's Modulus of Elasticity
Bend tests	1.	Elastic Limit in bending
	2.	Modulus of Elasticity in bending
	3.	Flexibility
Ductility	1.	Resistance to cold bending

He concluded that the clinical significance of a wire's performance was best evaluated by considering the flexibility, elastic limit in bending, ultimate tensile strength and ductility of the wire. The incorporation of a proof stress value into the Australian Standard T32 was suggested to provide more relevant information than the ultimate tensile strength. MASSON preferred bend testing although a general correlation between bend and tensile test data was noted.

Seven different wires were tested in this study. Specifically, they were the complete range of Wilcock wire (Special Plus, Special, Regular Plus and Regular grades), Dentaurum Super Spring Hard, Unisil and Red Elgiloy.

Unisil was shown to have the most suitable mechanical properties for archwire construction in Stage 1 of Begg orthodontic treatment. Wilcock Special Plus was the next most suitable wire.

It was also shown that Young's Modulus for stainless steel orthodontic wire varied with heat treatment and amount of cold work and that this variation must be taken into account when evaluating orthodontic wires.

BROCKHURST (1970) used the theory of simple bending to compare the performance of materials for spring members in dental appliances. It was shown mathematically and verified experimentally that the maximum performance of beams in elastic bending was proportional to the ratio of yield stress in tension to the (modulus of elasticity in tension)$^{\frac{3}{4}}$. The relationship was $y = 1.49x + 0.12$ where y equalled the value of the index calculated from tensile tests and x equalled the value of the index calculated from bend tests. Use of the index provided a method superior to tensile strength alone for comparing the bend properties of materials having differing moduli of elasticity.

STEPHENS and WATERS (1971) concluded that the ability of an unformed wire to resist permanent deformation depended on the amount of energy it could absorb elastically before plastic yielding occurred. A measure of this energy was determined from the stiffness of the wire and the minimum radius to which the wire could be formed and return to its original shape.

TWELFTREE (1973) investigated physical testing of orthodontic archwires. He interviewed orthodontists practising in Adelaide who stated that they required a wire which could be deformed the maximum amount without undergoing permanent deformation. Thus the inherent elastic properties of a wire would determine how effectively it functioned as an archwire in an orthodontic appliance.

TWELFTREE concluded that the elastic properties of a wire were best determined from a sensitive tensile testing apparatus and that the proportional limit was the most accurate measure of elastic properties. However, the proof stress value was found to be more useful for comparison of elastic properties of wires tested on different instruments.

During normal activation, it was found that a wire was strained near its proportional limit and the higher this limit the more truly elastically it would perform. The suggestion was made that the degree of stress relaxation in an elastically deformed wire may be important in evaluating the clinical effectiveness of the wire.

3.5 Metallographic Examination of Orthodontic Wires

BUSH, TAYLOR and PEYTON (1951) examined the relationship between the microstructure and chemical composition of dental gold wires. RICHMAN (1956) used metallographic techniques to investigate the structure of soldered and welded joints in orthodontic appliances. KOHL (1964) investigated the effect of heat treatment, soldering and welding on stainless steel, gold and chrome-cobalt alloys. Conventional optical and electron microscopic techniques were employed.

HARCOURT and MUNNS (1967) conducted metallographic examinations of stainless steel wires which had fractured in orthodontic appliances. Chemical etching revealed a fine, elongated structure. Non-metallic inclusions introduced during the manufacture of the steel were noted but they were not considered to detract from the mechanical properties.

WILLIAMS and VON FRAUNHOFER (1971) concluded that a detailed knowledge of the microstructure of wires would lead to further improvement in clinical properties. They noted that the microstructure of high tensile wire had been heavily distorted by cold work and was not revealed by simple etching procedures. An electrochemical method of etching which showed promising results was described.

3.6 Discussion of Literature Review

An orthodontic appliance depends for many functions on the elastic properties of the archwire (Section 3.3). However, in the Begg orthodontic technique, the elastic properties of the archwire are crucial for the efficient functioning of the appliance (Section 3.2).

It is generally agreed that the proportional limit is the best measure of the elastic properties of orthodontic wires (Section 3.4). Often the ultimate tensile strength is also quoted because it is well defined in a tensile test.

In the British Standard for Spring Wire (BRITISH STANDARD 2056, 1953) and the Australian Standard for Resilient Orthodontic Wire (AUSTRALIAN STANDARD T32) the ultimate tensile strength is the only parameter which may possibly be related to elastic properties. It is claimed that ultimate tensile strength is related to the elastic limit (DOCKING, 1965) and that as the ultimate tensile strength is increased, the proportional limit increases (NEWMAN, 1963). These, however, are statements without the support of experimental evidence. WILKINSON (1962) measured the proportional limit and ultimate tensile strength of a range of stainless steel wires and found that the ratio of these two properties was not constant. This conclusion was supported by MASSON (1969). Therefore, there are conflicting viewpoints which are difficult to resolve.

One factor which may explain this discrepancy is the difficulty of determining the proportional limit of a heavily cold worked stainless steel orthodontic wire (TWELFTREE, 1973). More sensitive equipment than that used by MASSON (1969) may be necessary to accurately determine whether a relationship exists.

The other major point of conjecture arising from the Literature Review is whether the proportional limit should be measured from a tensile test or a bend test. It is argued that because a wire is bent in use, the wire must be tested in bending (ANGELL, 1950; THUROW, 1962; MASSON, 1969). Evidence to support this view is provided only by ANGELL, who compared the performance of two gold wires which had very different moduli of elasticity. Tests on stainless steels and on wires with similar moduli of elasticity may have provided more conclusive evidence.

There is good evidence that performance in bending may be predicted from a tensile test. TAYLOR and PEYTON (1951) compared twelve wires and BROCKHURST (1970) predicted a relationship which was verified experimentally. MASSON (1969), who claimed a bend test would be more significant than a tensile test, found that there was a reasonable correlation between the data obtained from tensile and bend tests.

TWELFTREE (1973) compared the relationships between the inherent elastic properties of materials and the results obtained from tensile and bend tests. He concluded that because the assumptions that must be made in a bend test are much greater than those which are necessary for a tensile test, the results of the latter reflect the inherent elastic properties of a material more closely. Another advantage noted by this worker was that tensile testing equipment was usually more sophisticated than bend testing equipment and consequently more likely to produce reliable results.

From the evidence available, it is reasonable to conclude that the elastic properties of orthodontic wire are best measured from a tensile test.

In an attempt to overcome the practical difficulties of estimating the proportional limit of orthodontic wire, MASSON (1969) and TWELFTREE (1973) have suggested using a proof stress determination. This is a viewpoint which is not likely to arouse opposition because it is a recognized method of standardizing results of different investigators (DAVIS, TROXELL and WISKOCIL, 1964).

WILKINSON (1962) has correlated the hardness of stainless steel orthodontic wires with ultimate tensile strength and KEHL (1949) has described in general terms the relationship between Brinnell Hardness Number and ultimate tensile strength. BUSH, TAYLOR and PEYTON (1951) noted a relationship between Diamond Pyramid Hardness and proportional limit of gold alloy orthodontic wires. The constancy of the relationship found by WILKINSON for a broader range of wires and the relevance of the relationship between proportional limit and hardness of stainless steel wires requires further investigation.

The possible importance of stress relaxation of orthodontic wires has been noted by TWELFTREE (1973). No further information on this subject is available and further investigation is warranted.

The significance of modulus of elasticity has received little attention in the literature. This property of materials is relatively constant and determines the stiffness of wires. It is important to measure the modulus of elasticity because variations in applied force arising from different elastic moduli may be compensated for by altering the diameter of the wire (WILKINSON, 1960).

Metallographic investigations of orthodontic wires have concentrated on the effects of heat on the structure (RICHMAN, 1956; KOHL, 1964) and the causes of failure (HARCOURT and MUNNS, 1967). WILLIAMS and VON FRAUNHOFER (1971) concluded that chemical etching would not reveal the grossly distorted structures of heavily cold worked materials and that more sophisticated procedures were necessary. They emphasised however, that advantages could be gained if microstructures were correlated with mechanical properties.

In summary, it may be stated that:-

1) the elastic properties of a wire determine its effectiveness in the Begg orthodontic appliance.
2) the tensile proportional limit is a satisfactory measure of elastic properties but the proof stress may be a more reproducible quantity.
3) a relationship may exist between ultimate tensile strength and elastic properties.
4) hardness may be a useful property by which to compare orthodontic wires.
5) the importance of stress relaxation in orthodontic wires requires investigation.
6) valuable information may be obtained from an investigation of the microstructure of orthodontic wires.

4. AIMS OF THE EXPERIMENTAL INVESTIGATION

The aims of the experimental investigations are:

1. To determine the ultimate tensile strength, proportional limit and proof stress values of a range of wires suitable for archwire construction in Stage 1 of Begg orthodontic treatment from tensile tests on a sensitive instrument.

2. To compare these results and evaluate the usefulness of each measurement as an indication of the clinical effectiveness of the wire.

3. To investigate the occurrence of stress relaxation in selected wires at the stress levels produced in clinical use.

4. To develop a method for comparative study of the stress relaxation characteristics of different wires.

5. To measure the hardness of the wires and evaluate the relevance of this property in comparative testing of orthodontic wires.

6. To examine the structure of the wires using optical metallographic techniques in order to evaluate the usefulness of these techniques in examining orthodontic wires and to relate the structure of the material with its mechanical properties.

5. MATERIALS AND METHODS

5.1 Wires Tested

Two criteria were used to select wires for examination and testing in the present programme. They had to be (1) available through commercial sources in Adelaide, South Australia, and (2) commonly used or recommended for fabricating Stage 1 Begg archwires by practising orthodontists in Australia. The latter criterion assumes a nominal diameter of 0.016 ins.

5.1.1 Wilcock Wires

This group of wires is produced by A.J. Wilcock at Whittlesea, Victoria, Australia. Several grades are available. The Special and Special Plus grades are used in Adelaide (TWELFTREE, 1973) and Sydney (RICKLEMAN, 1967) and were automatic choices for study.

In addition, Wilcock produces two higher grades of wire referred to as Premium and Premium Plus. He claims that these grades exceed the requirement for a type D wire which is that the ultimate tensile strength exceed 391,000 p.s.i. (AUSTRALIAN STANDARD T32). For this reason, these two wires were also selected for study.

All Wilcock wires have the same composition and it appears that the different properties are generated by varying the thermo-mechanical treatments used in their manufacture. The wires can be regarded as 18-8 austenitic stainless steel.

The nominal composition complies with British Standard 2056 (1953), namely carbon 0.16%* (max), silicon 0.20% (min), manganese 2.0%

* Throughout this thesis, compositions are reported in wt%.

(max), nickel 7.10%, chromium 17-20%, nickel plus chromium 25% (min), sulphur 0.045% (max) and phosphorus 0.045%.

Supplies of the Special and Special Plus grades were randomly selected from the store of the Orthodontic Department of the Royal Adelaide Hospital. The Premium and Premium Plus wires were purchased from A.J. Wilcock.

The Batch Numbers of the samples which were used appear in Table 1.

TABLE 1

GRADE	BATCH NUMBERS
Premium Plus	DH. RKC
Premium	LH. ROC
Special Plus	WI. ROC; BI/ROH
Special	BT/RCH; EO.RCA TI.RCI

To further investigate the properties and structure of Wilcock wires, samples of the Special Plus wire were annealed. This grade was selected for further study because it is recommended by BEGG (1971) as the only wire suitable for use in his technique. The wire was annealed by heating samples in an inert gas (argon) atmosphere. Results of these investigations appear in Appendix 1.

5.1.2 Unisil Wire

This wire was selected because it is used in Sydney (RICKLEMAN, 1967) and has been highly recommended by MASSON (1969). It is marketed by the Unitek Corporation, Monrovia, California. The wire is a 15-5 precipitation hardening stainless steel (MASSON, 1969) with the following composition: - carbon 0.142%; manganese 1.0%; phosphorus 0.027%, sulphur 0.013%; silicon 0.32%; chromium 15.65%; nickel 4.38%; molybdenum 2.68%; copper 0.12%; nitrogen 0.124%; and iron balance.

A supply of this wire, which is not identified with a batch number, was obtained from the Unitek representative in Adelaide.

5.1.3 <u>Dentaurum Wire</u>

The Dentaurum company markets a wire designated Super Special Spring Hard which is claimed to have suitable properties for use in the construction of Begg Stage I archwires. It has been classified a Type D resilient orthodontic wire (AUSTRALIAN STANDARD T32) by the Standards Association of Australia. MASSON (1969) noted that Super Spring Hard wire is a 17 - 7 precipitation-hardening stainless steel with a composition of carbon 0.07%, chromium 16.5% and nickel plus aluminium 6.5%. It is likely that Super Special Spring Hard wire has a similar composition.

5.1.4 <u>Elgiloy Wire</u>

The Rocky Mountain Dental Products Company of Denver, Colorado, has developed Elgiloy wires for use in orthodontics. Elgiloy is a patented cobalt-base alloy compounded of eight elements. Its nominal composition is cobalt 40%; chromium 20%; nickel 15%; molybdenum 7%; manganese 2%; beryllium 0.04%; carbon 0.15% and iron 15.81%. This alloy work hardens very rapidly and undergoes an age hardening reaction at temperatures between 260°C and 650°C following a solution heat treatment at 1100°C (SKINNER and PHILLIPS, 1967).

These wires are offered in many cross-sectional shapes and dimensions for a wide range of uses. There are four grades of Elgiloy wires - red, green, yellow and blue, each representing different degrees of cold work. The company recommends the yellow and green grades as suitable for use in the Begg orthodontic appliance. The wires are supplied in the 'soft' condition. The archwire is fabricated with the wire in this state and then heat treated to improve the spring qualities. Therefore, the samples were tested following a heat treatment recommended by the manufacturer. The method chosen was to heat the wire at 500°C for 10 min in a furnace.

Supplies were ordered from the Australian distributor. Batch numbers were not supplied.

5.2 Testing Equipment

5.2.1 Instron Universal Testing Instrument (Fig. 11)

(Floor Model TT-D, Standard Metric, Operating Instructions, 1967)

This instrument was used to subject specimens to a tensile test. It consists of two cross-heads, one of which is driven by a screw thread supported by a rigid frame. Load cells are inserted into the upper fixed cross-head. The specimen is supported between these load cells and the moveable cross-head and is subjected to a tensile load as the moveable cross-head is lowered. The load on the specimen is recorded from the load cell onto a moving chart by means of a pen recorder. The cross-head and the chart speed are both constant. Therefore, extension can also be obtained from the chart record. If desired, the extension can be recorded on the chart by an extensometer attached to the specimen.

Load Weighing System

An Instron Tension Load Cell Type 2511-104, Model No. A30-40 was used. This cell has full scale ranges of 1, 2, 5, 10, 20 and 50 kg. The applied load on the cell causes a proportional change in the resistance of the strain gauges within the cell. The resulting signal is amplified, rectified to D.C. and used to drive a high speed recorder. The amplifier circuit also incorporates a flexible means of balancing the load cell to compensate for the weight of jaws, fixtures and the samples themselves. The sensitivity of the amplifier may be changed in calibrated steps of 1, 2, 5, 10, 20 and 50, enabling the load cell to provide a number of full scale loads. Another control varies the sensitivity continuously between any of these steps to calibrate the

Fig.11 Instron Universal Testing Instrument

A - Load Cell

B - Vee Wire Grips

C - Extensometer

D - Moving Cross-head

E - Recording Chart


A
INSTRON
B
C
E
D

instrument for any desired value of full scale load.

The load cell is calibrated by hanging small weights from the upper coupling and adjusting the sensitivity. Only the lowest load range of the cell needs to be calibrated to be effective for all the other ranges. For example, this cell is calibrated by using a 1 or 2 kg weight and adjusting the sensitivity to provide full scale deflection.

The accuracy of the load weighing system is ±½% of indicated load, or ±¼% of recorder scale in use, whichever is the greater for all load ranges. The speed of response is mainly limited by the pen speed of the recorder, because the load cells themselves have a high frequency response. The load cells exhibit very little deflection under the applied load, and in many cases, the motion of the pulling jaw may be used to determine the extension of the samples.

The load weighing system exhibits practically no mechanical inertia. Therefore, its action does not significantly influence the properties of the sample to be measured.

Cross-head Drive System

The moving cross-head is operated by a positional servomechanism that incorporates an amplidyne power drive and synchro-control elements. The cross-head guidance system has excellent lateral stiffness. Cast iron shoes embedded in the cross-head travel along one inch steel bars. These shoes are preloaded and adjustable to maintain cross-head alignment.

The selection of the cross-head speed is governed by the characteristics of the sample and the desired test conditions. Usually the desired testing rate is specified in terms of the "percent of sample extension per minute".

Extension Recording System

The recorder chart is driven from a synchronous motor through a set of change gears that provides a ratio selection of 250:1 in chart speed. Because of their synchronous operation individual motions of the chart and cross-head correspond. In most tests the time axis of the chart can be an accurate measure of the grip position and, consequently, sample extension. This close relationship is maintained by virtue of the low inherent deflection of the load cells and by the almost total elimination of backlash in the cross-head driving assembly.

This method of extension recording is particularly important when testing wire samples when the weight of strain measuring devices is likely to affect the test results. However, when testing samples at high loads, the residual deflections of the load cells and the machine, and the slippage of the sample from the grips, may be sufficient to affect the accuracy of the method. Some of these errors can be compensated for by direct calibration of machine deflection.

To completely remove the abovementioned sources of error, separate strain measuring devices, e.g. extensometers, may be attached to the sample to measure the strain directly. In these circumstances the chart motion is operated under the control of the extensometer using the Servo Chart Drive System. Therefore, the recorder measures load against actual extension of the gauge length rather than load against time.

Extensometer

The strain gauge extensometer used was the Instron G-51-11 M. This has a gauge length of 25 mm and a maximum strain of 10%. It weighed 42 g.

As the clamps of this particular extensometer will only accommodate round specimens one-eighth inch in diameter, special brass plungers were constructed to replace the original plastic type. These enabled the clamps to grip the diameter wire to be tested. (Fig. 12).

Zero Suppression

To increase the accuracy of the information obtained from the tensile test, any portion or the whole of the load scale can be magnified using the zero suppression technique. This procedure unbalances the load cell a known amount to suppress the zero load point off the scale of the chart. The suppression can be gradually introduced in increments as the specimen is being tested, and the zero point suppressed further and further off the scale as full scale deflection of the recorder is reached. In this manner the load scale is greatly magnified.

Grips

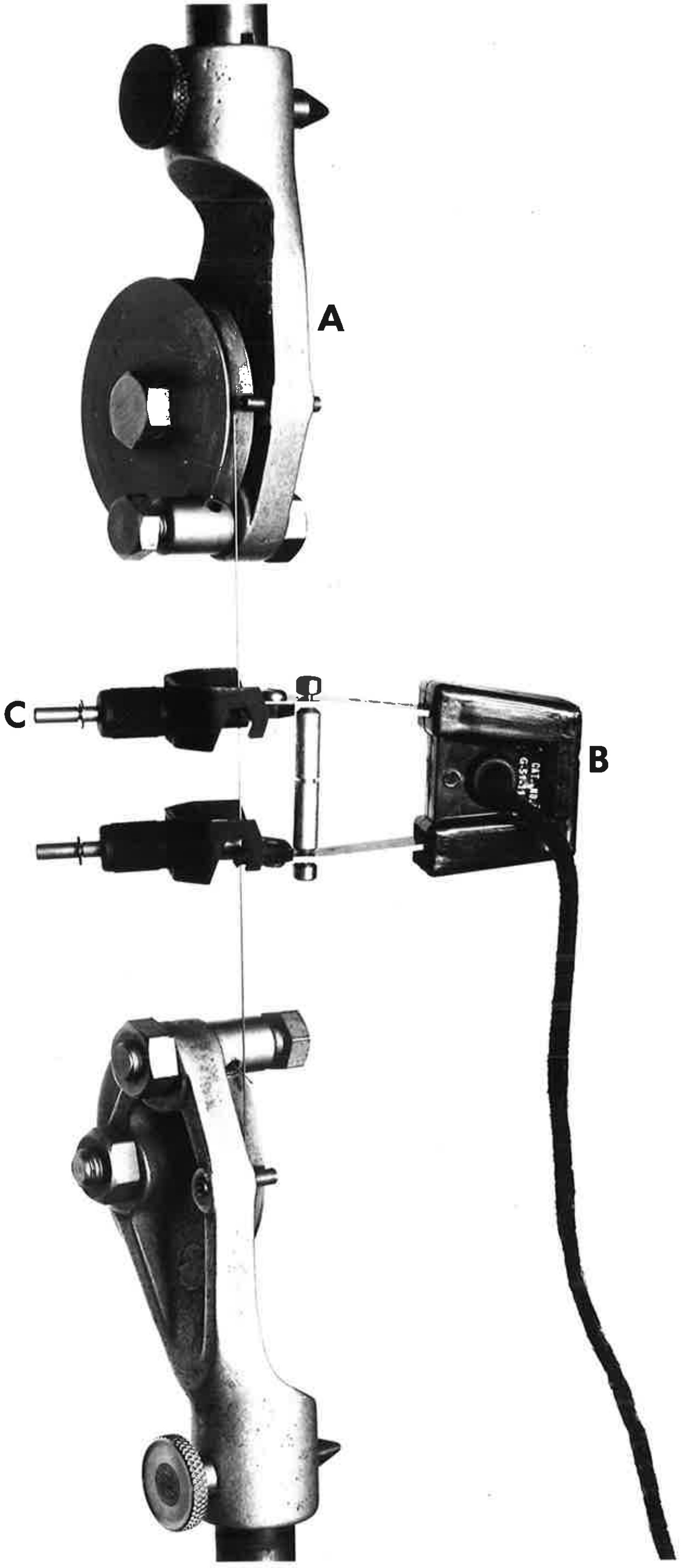
The grips which were found most suitable were the Hounsfield Vee Wire Grips (Fig. 13). They were attached to the cross-heads of the Instron Universal Testing Instrument. It was found that only infre-

Fig.12 Extensometer in position

A - Vee Wire Grips

B - Extensometer

C - Brass Plungers


A
B
C

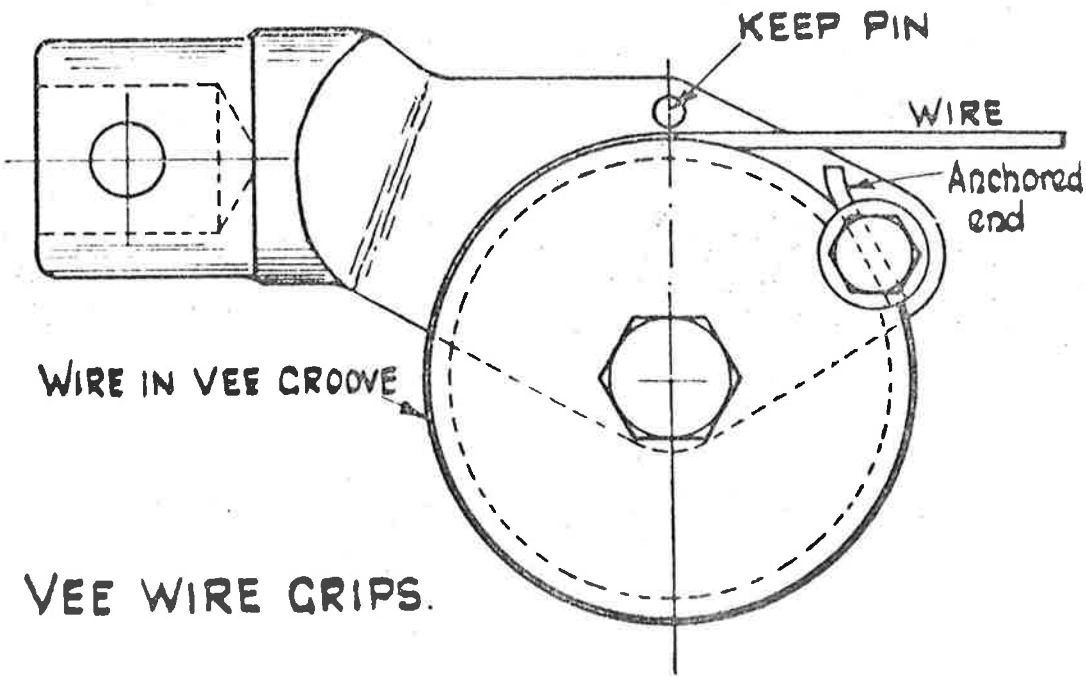


Fig.13

quently did the wire not fracture within the gauge length. Tests were discarded if fracture occurred in any section of the wire in contact with the grip.

5.2.2 Leitz Miniload Hardness Tester

This instrument was used to measure the hardness of the wires. It is designed to determine the hardness of small areas. In this test, a diamond of precise dimensions impinged on the specimen under a known load. The size of the indentation was measured to the nearest 0.1 microns using an ocular eyepiece. The hardness value was read from charts which related the average length of the diagonal of the indentation to the hardness.

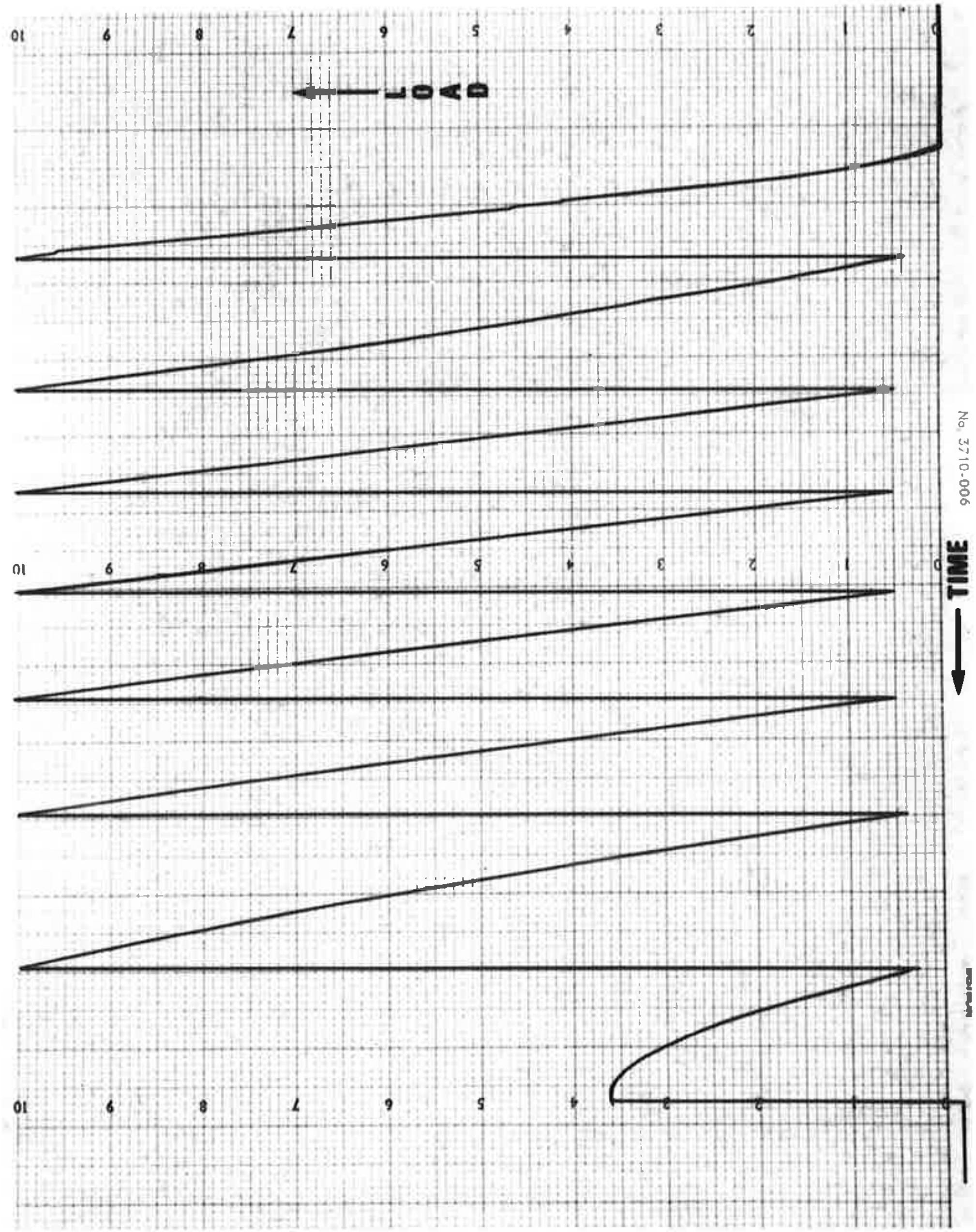
5.3 Tensile Tests

Each wire was subjected to two types of tensile test on the Instron Universal Testing Instrument. Each specimen was initially loaded to 0.8 kg by manually operating the cross-head. The load scale was then balanced to zero. This operation straightened the section of wire and provided a standard base from which to begin the test. The tensile strain rate for all tests was 1 mm/min.

The first series used cross-head movement as a measure of extension. The zero suppression device was used in 5 kg steps which had the advantage of greatly magnifying the graph without losing the smoothness of the curve (Fig. 14). From this graph it was possible to estimate the load at which the curve deviated from a straight line, i.e. where elastic behaviour ceased. The horizontal offset of each section of the curve to the other was measured. After allowing for 'take-up' of slack in the specimen grips, it was usually found that this measurement was initially constant, indicating that successive sections of the curve were parallel, i.e. a section of constant slope. The first point at which parallelism of the sections was lost was taken as the limit of proportionality. The stress corresponding to this load was the proportional limit. Proof stress determinations were made by constructing offsets at .02%, .05% and .1% strain relative to the section of constant slope.

Ultimate tensile strength was calculated from the load at which fracture occurred.

The second series of tests used the extensometer to measure

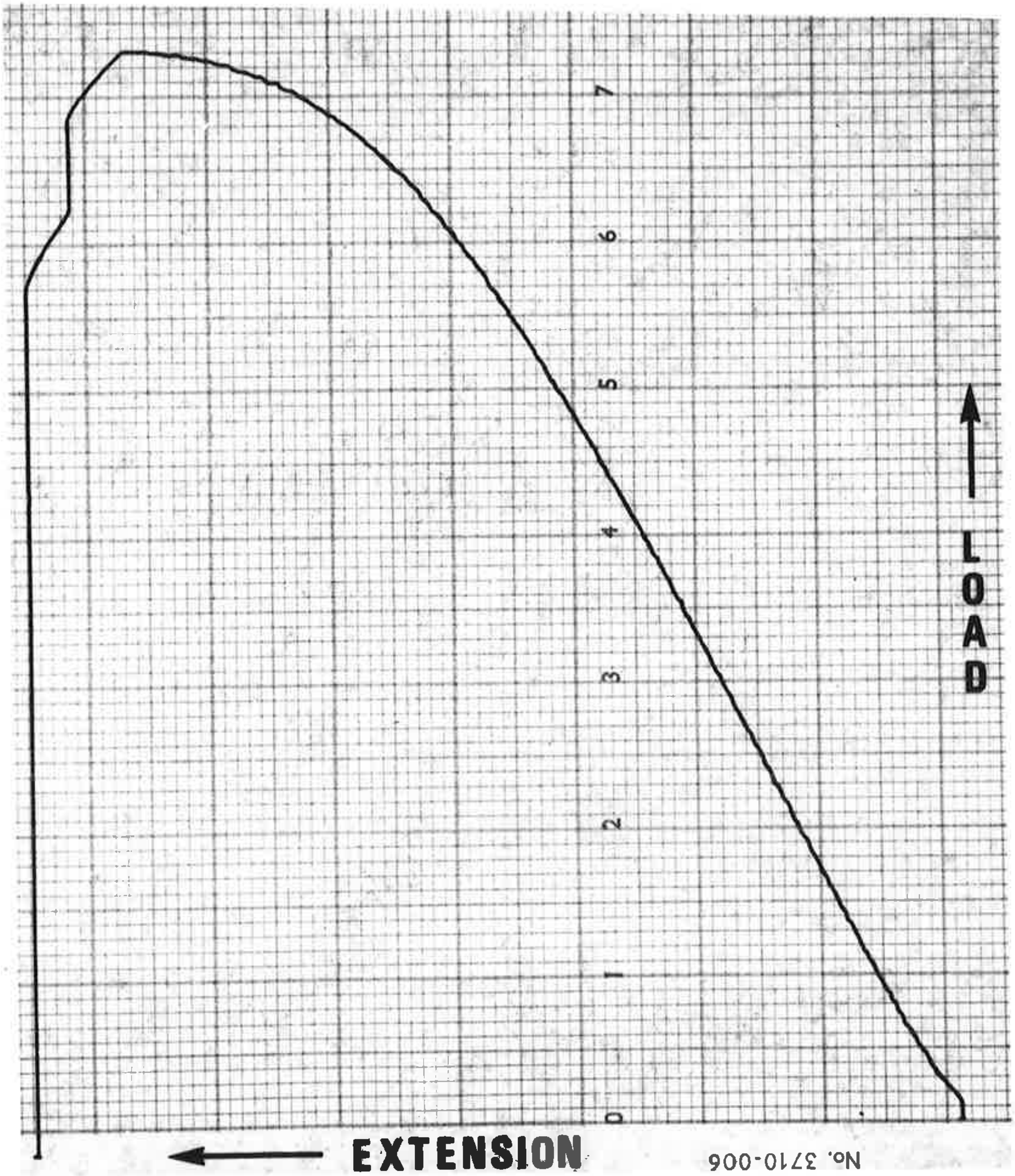


Tensile Test with Zero Suppression

Fig.14

extension of the wire. The resultant curve (Fig. 15) was found to be very accurate for measuring specimen strain but the proportional limit could not be accurately determined. This technique was used to determine the modulus of elasticity of the specimen. A section of the curve within the elastic range was selected. The change in stress over this section was divided by the corresponding change in strain to calculate Young's Modulus.

Some difficulty was experienced in ensuring the more brittle wires, namely Wilcock Premium Plus and Green Elgiloy, fractured within the gauge length. These wires failed prematurely at the point where the screw of the Vee grip contacted the wire. This problem was partially overcome by feeding the wire into the screw casing backwards and winding it around the casing before it entered the Vee groove of the grip. Premium Plus was gripped satisfactorily by this method but Green Elgiloy continued to fracture.



Tensile Test with Extensometer

Fig.15

5.4 Stress Relaxation Tests

The Instron Universal Testing Instrument was used to measure stress relaxation in orthodontic wires. Specimens were inserted according to the procedure for a standard tensile test. The cross-head was lowered until the stress in the wire reached a predetermined value. Motion of the cross-head was stopped to maintain constant strain. Any change of the stress in the wire was measured as a change in load by the load cell. Use of the zero suppression device permitted magnification of the load scale to a full scale deflection of 5 kg.

Preliminary experiments were performed on Special Plus and Unisil to determine whether these wires demonstrated measurable relaxation. An initial stress corresponding to 30 kg load was arbitrarily chosen. The load was recorded at intervals over a five day period.

From the results of these preliminary tests, experimental parameters were defined for conducting comparative tests on the complete range of wires. It was decided to load specimens to 20 kg and record the decrease in stress for three days.

An initial stress corresponding to a load of 20 kg was chosen for the following reasons.

1. This level of stress corresponds to the average maximum stress produced at the outer fibres of a wire in the area of an activated anchorage bend (TWELFTREE, 1973).
2. An alternative method for comparing relaxation characteristics is to select an initial stress value related to the proportional limit

of the material. However, the proportional limit of orthodontic wire is difficult to measure (Section 5.3) and it is considered that a fixed initial load from which to commence stress relaxation tests provides more standardized results.

3. A 20 kg load corresponds closely to the proportional limit of many of the wires. The plastic strain for all wires at this load is less than 0.05% (Section 6.1) and it is possible this small plastic strain might influence the stress relaxation properties. However, this extra work hardening is insignificant when compared with the extensive cold work, revealed by metallographic examination (Section 6.4), that these wires have already experienced during the drawing operation.

4. At a load of 20 kg it is possible to magnify the load scale on the Instron to a full scale deflection of 2 kg and increase the sensitivity of the reading.

It was found that temperature variations affected the results. Although the thermal coefficient of expansion of stainless steel wire is only $9.6 \times 10^{-6}/^{o}F$, each degree change in temperature would vary the load by approximately 0.035 - 0.040 kg. Consequently, it was necessary to maintain constant temperature for the period of each test or to compensate for the thermal changes.

The change in stress was measured for three days. Prolonging the tests would take more time than was available in which to use the Instron. However, it was considered that this period was sufficient to obtain qualitative comparisons of the initial stress relaxation behaviour of the wires.

To obtain an indication of the long term effects of stress relaxation, 160 cm lengths of Wilcock Special Plus and Unisil wires were loaded with dead weights of 30 kg. The specimens were left for 16 weeks. After this time, the effect of the stress on the original form of the wire was observed.

This series was not analogous to the previous experiments. The stress was kept constant and the strain permitted to increase. It was, in effect, a creep test.

5.5 Hardness Tests

The hardness of all wires was determined using a Leitz Miniload Hardness Tester (Section 5.2.2). A Vickers diamond indenter with a 0.3 kg test weight was used.

The mounted sections of wire which had been prepared for the metallographic examination were used (Section 5.6). These etched specimens were briefly polished on a 1 micron diamond polishing lap in preparation for the hardness determination.

A standardized procedure was adopted in making the indentation, so that only six indentations per specimen were necessary to obtain consistent results. The recommended time of 25 seconds between releasing the diamond and reactivating the mechanism was strictly adhered to. This was the most important factor in the standardized procedure.

5.6 Metallographic Examinations of Wires

The microstructure of the complete range of stainless steel wires included in this study was optically examined. A short length of each wire was bent to a predetermined shape to enable a study of the longitudinal and cross-sectional structure. Specimens were mounted in bakelite according to standard metallographic practice. The samples were then ground on 420 and 600 grade wet and dry paper and polished on a 6 micron diamond polishing lap, lubricated with kerosine. Final polishing was achieved using a 1 micron diamond lap. The polished specimens were ultrasonically cleaned in baths of kerosine and alcohol and dried in a blast of warm air.

At this stage of preparation, the wire had a smooth mirror-like appearance virtually free from scratches. To reveal the micro-structure it was necessary to etch the surface.

A selection of etching agents was provided in standard texts on metallographic laboratory practice (see KEHL, 1949). After much trial and error a mixture of 5 gm ferric chloride, 50 ml concentrated hydrochloric acid and 100 ml of water was found to give a satisfactory etch.

The clean and dry polished surface of the wire was etched for 3 seconds by swabbing the surface with a cotton wool ball soaked in the etching agent. All traces of the etchant were immediately removed with warm water. The specimen was then washed in alcohol and dried in a blast of warm air. The wire was then ready for examination under the optical microscope.

A Zeiss Ultraphot II Camera Microscope was used to examine the specimens and photograph the microstructures at a magnification of 300X.

6. RESULTS

6.1 Tensile Tests

6.1.1 Ultimate Tensile Strength

Values for ultimate tensile strength are reported in Table 2 in British and Système Internationale units. The standard deviation of each value is included.

TABLE 2

WIRE	ULTIMATE TENSILE STRENGTH			
	p.s.i. x 10^{-3}		MPa	
	Mean	S.D.	Mean	S.D.
Premium Plus	441	2.1	3070	15
Premium	412	0.5	2870	3
Special Plus	401	1.7	2970	12
Special	377	11.0	2630	77
Unisil	409	8.9	2850	62
Dentaurum	384	0.7	2680	5
Yellow Elgiloy	287	5.3	2000	37

From these results, Wilcock Premium Plus, Premium and Special Plus and Unisil wires could be classified Type D wires (AUSTRALIAN STANDARD T32).

Wilcock Special and Dentaurum Super Special Spring Hard wires achieved a Type C classification. It must be noted, however, that if the original preload of 0.8 kg was included, the U.T.S. for the Dentaurum wire would have been 393,000 p.s.i. (2740 MPa) thereby giving this wire a Type D classification. The Commonwealth Bureau of Dental Standards has classified Super Special Spring Hard a Type D wire although the U.T.S. they achieved was 422,000 p.s.i. (2940 MPa).

The standard deviations of four of the wires, Premium Plus, Premium, Special Plus and Dentaurum, were very much lower than for Wilcock Special, Unisil and Yellow Elgiloy wires.

Tensile tests were undertaken on samples of Green Elgiloy but valid results could not be obtained as the specimen repeatedly fractured at the grips. Furthermore, as only one coil of this wire was available, this supply was rapidly exhausted.

6.1.2 Proportional Limit

The values of the proportional limit of each wire are recorded in Table 3.

TABLE 3

WIRE	PROPORTIONAL LIMIT			
	p.s.i. x 10^{-3}		MPa	
	Mean	S.D.	Mean	S.D.
Premium Plus	360	9.0	2510	63
Premium	275	10.5	1920	73
Special Plus	219	1.6	1530	11
Special	212	14.0	1480	98
Unisil	232	13.6	1620	95
Dentaurum	209	6.2	1460	43
Yellow Elgiloy	198	31.4	1380	219

These values were calculated by the method described in Chapter 5.3. However, this method was not completely satisfactory because two of the six tests on Wilcock Premium Plus and Yellow Elgiloy wire did not produce a straight line portion of the stress-strain curve.

Premium Plus and Premium wires had significantly higher proportional limits than the other wires. The smaller differences between the other wires could not be considered significant when the large values of the standard deviations were taken into account.

The standard deviation of the values of proportional limit were much higher than for the ultimate tensile strengths. Special Plus wire was the most consistent performer while Yellow Elgiloy was found to be quite variable. However, a more detailed examination of the results on this wire revealed that if one run was excluded, the mean proportional limit increased to 214,000 p.s.i. (1490 MPa) and the standard deviation reduced to 14,500 p.s.i. (103 MPa).

6.1.3 Proof Stress

The Proof Stress of each wire was calculated at 0.02%, 0.05% and 0.1% plastic strain. The results are detailed in Tables 4, 5 and 6, respectively.

TABLE 4

WIRE	PROOF STRESS (0.02% strain)			
	p.s.i. x 10^{-3}		MPa	
	Mean	S.D.	Mean	S.D.
Premium Plus	375	4.8	2610	33
Premium	308	10.5	2150	73
Special Plus	246	4.7	1710	32
Special	249	18.6	1740	129
Unisil	260	11.8	1810	82
Dentaurum	245	6.1	1710	43
Yellow Elgiloy	209	31.5	1460	220

TABLE 5

WIRE	PROOF STRESS (0.05% strain)			
	p.s.i. x 10^{-3}		MPa	
	Mean	S.D.	Mean	S.D.
Premium Plus	388	6.0	2700	42
Premium	337	7.0	2350	48
Special Plus	279	7.2	1940	50
Special	275	18.6	1920	130
Unisil	292	14.2	2030	99
Dentaurum	273	4.9	1900	34
Yellow Elgiloy	224	31.2	1560	217

TABLE 6

WIRE	PROOF STRESS (0.1% strain)			
	p.s.i. x 10^{-3}		MPa	
	Mean	S.D.	Mean	S.D.
Premium Plus	406	4.2	2830	29
Premium	362	3.3	2520	23
Special Plus	310	9.1	2160	63
Special	313	16.8	2180	117
Unisil	326	14.0	2270	98
Dentaurum	304	2.6	2120	18
Yellow Elgiloy	239	30.7	1670	214

Premium Plus and Premium wires maintained their significant differences from the other wires over the range of proof stress determinations. The standard deviations remained high but tended to decrease with increasing values of the strain at which the proof stress was determined. The differences in proof stress of Special Plus, Special, Unisil and Dentaurum wires remained insignificant. However, the proof stress of Yellow Elgiloy wire became significantly less as the strain level increased.

6.1.4 Modulus of Elasticity

Values of Young's moduli of elasticity are given in Table 7.

TABLE 7

WIRE	MODULUS OF ELASTICITY			
	p.s.i. x 10^{-6}		MPa x 10^{-4}	
	Mean	S.D.	Mean	S.D.
Premium Plus	24.9	0.81	17.4	0.56
Premium	24.4	0.90	17.0	0.63
Special Plus	23.5	0.61	16.4	0.43
Special	21.5	0.71	15.0	0.50
Unisil	22.0	1.27	15.3	0.88
Dentaurum	22.9	0.83	16.0	0.58
Yellow Elgiloy	24.3	1.22	16.9	0.85

The value of the modulus increased through the range of Wilcock wires from Special to Premium Plus. Unisil and Dentaurum Super Special Spring Hard had values between those of Wilcock Special and Special Plus. The modulus of elasticity of Yellow Elgiloy was similar to the value for Wilcock Premium Plus.

6.1.5 Interrelationship of tensile properties

Table 8 shows the relationship between ultimate tensile strength and the other tensile properties. The values of proportional limit and the proof stresses are expressed as a percentage of the ultimate tensile strength.

TABLE 8

WIRE	PROPORTIONAL LIMIT	0.02% PROOF STRESS	0.05% PROOF STRESS	0.1% PROOF STRESS
Premium Plus	82%	85%	88%	92%
Premium	67%	75%	82%	88%
Special Plus	55%	61%	70%	77%
Special	56%	66%	73%	83%
Unisil	57%	64%	71%	80%
Dentaurum	54%	64%	71%	79%
Yellow Elgiloy	69%	73%	78%	83%

From Tables 3, 4, 5 and 6 it can be seen that the values of proportional limit and proof stress increased as the ultimate tensile strength increased. The ratio between these properties was not constant (Table 8) but some trends were apparent. The ratio between proportional limit and ultimate tensile strength of Special Plus, Special, Unisil and Dentaurum wires was remarkably constant. A similar relationship was evident between the ultimate tensile strength and the proof stresses of these wires.

As the strain level at which the proof stress was determined increased, the ratio between the proof stress and ultimate tensile strength of all wires became more constant. At 0.02% strain, the range of percentages was from 61% to 85% whereas at the 0.1% level, the range became 79% to 92%.

6.2 Stress Relaxation Tests

6.2.1 Results of Preliminary Tests

Samples of Unisil and Wilcock Special Plus were loaded to 30kg (equivalent to 2,288 MPa or 328,000 p.s.i.) on the Instron Universal Testing Instrument. Strain was held constant and the load measured at intervals for five days. There was an initial rapid decrease in load but the rate of relaxation decreased markedly after approximately five minutes. Additional relaxation was measured at intervals of several hours. Load was converted to stress and these values were plotted against time (Fig. 16), producing curves showing the stress relaxation behaviour.

To test the theory that the wire might respond according to the ideal behaviour of the Maxwell Model, the natural logarithm of the stress was plotted against time (Fig. 17). It can be readily seen that the rate of relaxation for the first few hours was much greater than the rate for the next 50 hours.

A portion of the initial drop in load in the first five minutes can be attributed to machine error. However, as the two wires tested produced different effects, a significant amount of this initial relaxation was attributed to the stress relaxation characteristics of the wire. The rate of relaxation was relatively rapid for the next 20 hours. After this time, the rate was relatively constant and the response approximated the ideal behaviour of the Maxwell Model.

No mechanism is proposed to explain the stress relaxation

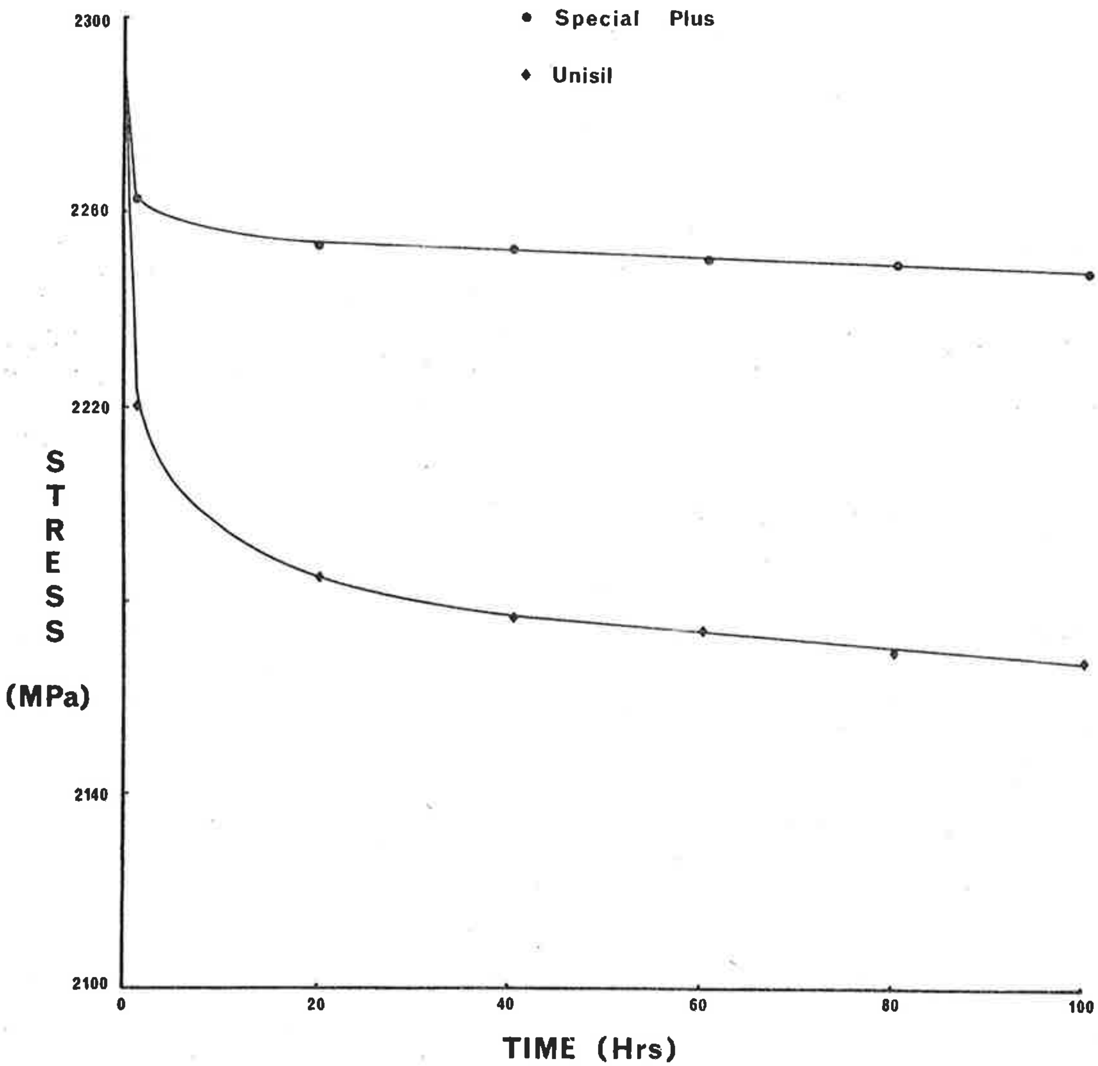
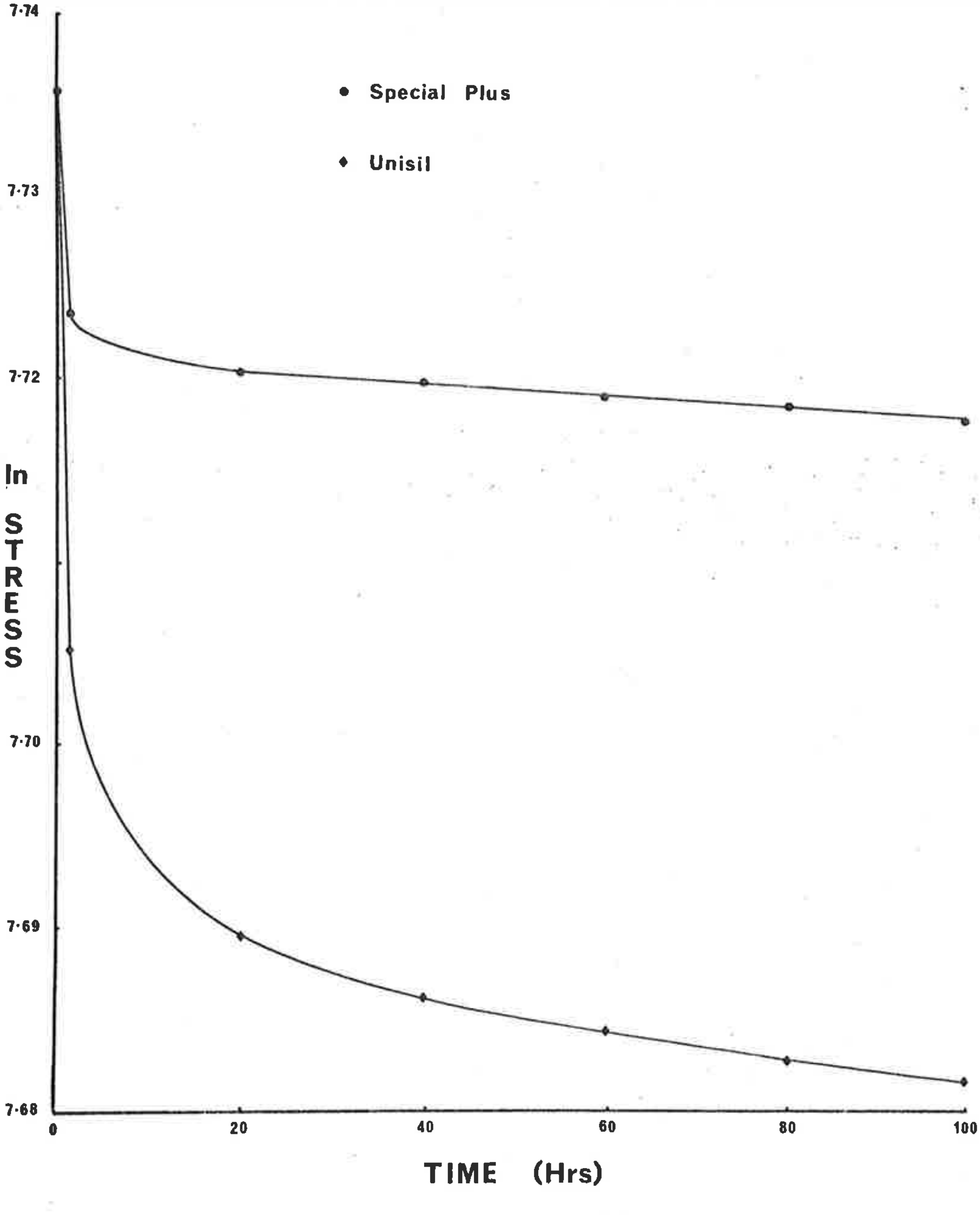

Special Plus
Unisil
2300
2260
2220
2140
2100
STRESS
(MPa)
0
20
40
60
80
100
TIME (Hrs)

Fig.16



7·74
7·73
7·72
7·70
7·69
7·68
• Special Plus
♦ Unisil
ln STRESS
0
20
40
60
80
100
TIME (Hrs)

Fig.17

behaviour of the wires. The important conclusions that can be drawn from these results are that orthodontic wires do exhibit stress relaxation and that the amount of stress relaxation varies with different wires.

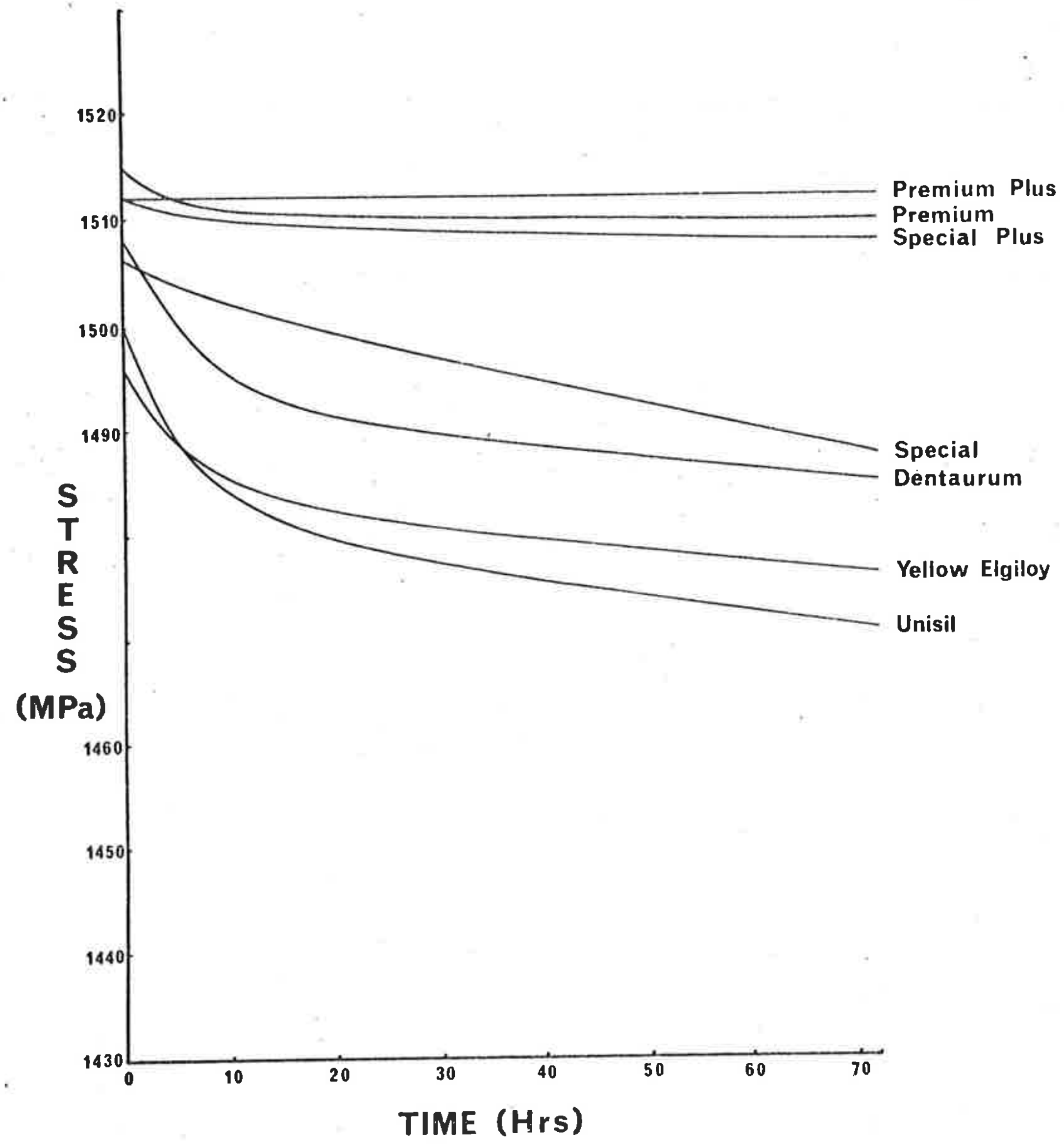
6.2.2 Results of Comparative Tests

Stress relaxation tests were performed on all wires by the procedure described in Section 5.4. Only one complete test on each wire was undertaken but in order to examine the reproducability of the results, three additional determinations of the extent of stress relaxation over a ten minute period were conducted.

Figure 18 displays the results as stress plotted against time. The plots to 10 minutes represent the mean values of the four runs while the curve beyond this time is the result of only one experiment. However, the relatively constant relationship of the behaviour of one wire to the other suggests that the latter portions of the curves are probably valid representations of the behaviour of each wire.

It can be seen that all wires responded in a similar manner. There was an initial rapid drop in stress for a few minutes but the rate of relaxation decreased during the next 24 hours. After 24 hours the slope of the curve became relatively constant.

Comparative conclusions can probably be best drawn from Fig. 18. However, the results are also displayed in Table 9 which expresses the stress after 10 minutes, 24 hours and 72 hours as a percentage of the original stress. These figures give a more quantitative idea of the



1520
1510
1500
1490
1460
1450
1440
1430
STRESS (MPa)
0
10
20
30
40
50
60
70
TIME (Hrs)
Premium Plus
Premium
Special Plus
Special
Dentaurum
Yellow Elgiloy
Unisil

Fig.18

TABLE 9

WIRE	STRESS at 10 mins	STRESS at 24 hrs	STRESS at 72 hrs
Premium Plus	98.95%	99.25%	99.30%
Premium	99.30%	99.00%	99.00%
Special Plus	99.15%	98.95%	98.85%
Special	98.70%	98.20%	97.50%
Unisil	98.35%	96.90%	96.40%
Dentaurum	98.85%	97.65%	97.35%
Yellow Elgiloy	98.05%	97.10%	96.75%

stress relaxation behaviour of each wire over a three day period.

The behaviour of three wires, Wilcock Premium Plus, Premium and Special Plus was significantly different from the other wires. These wires exhibited much less stress relaxation over the period of the test. Although the maximum percentage reduction of stress shown in the tests was only 3.60%, the curves in Fig. 18 indicate that the relative behaviour of each wire would continue for a much longer period.

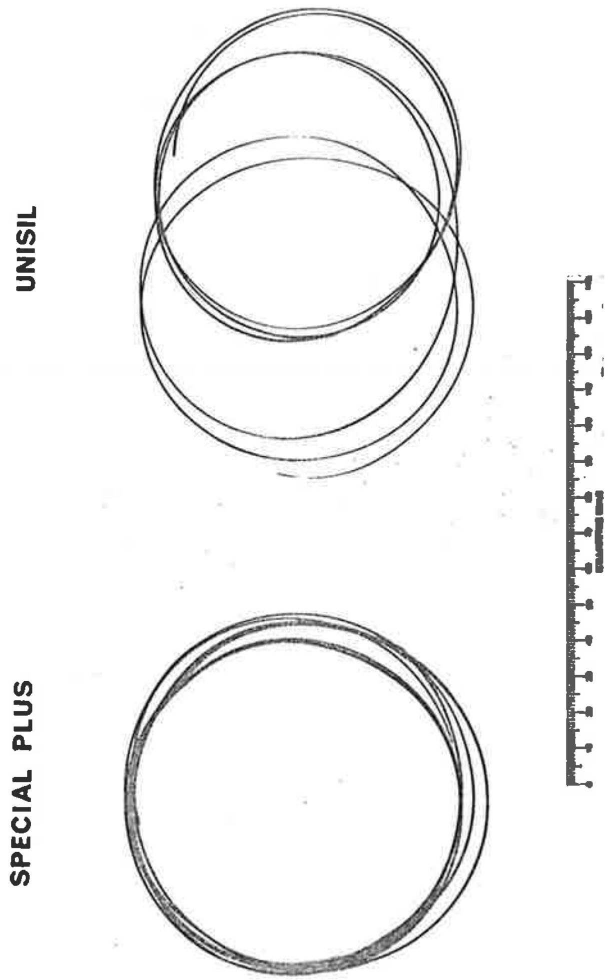
It may be unreliable to extrapolate results over three days for a 3 or 6 month period. However, to provide preliminary information on the possible effects of stress relaxation over a longer period, the results have been extrapolated and the relevant data appears in Appendix 2.

6.2.3 Long Term Observations on Stress Relaxation

This series was designed to study the long term effects of stress relaxation. Although it was not possible to maintain a constant strain with the apparatus, the study was permitted to continue to observe the effect of continued stress on the coil size of the samples.

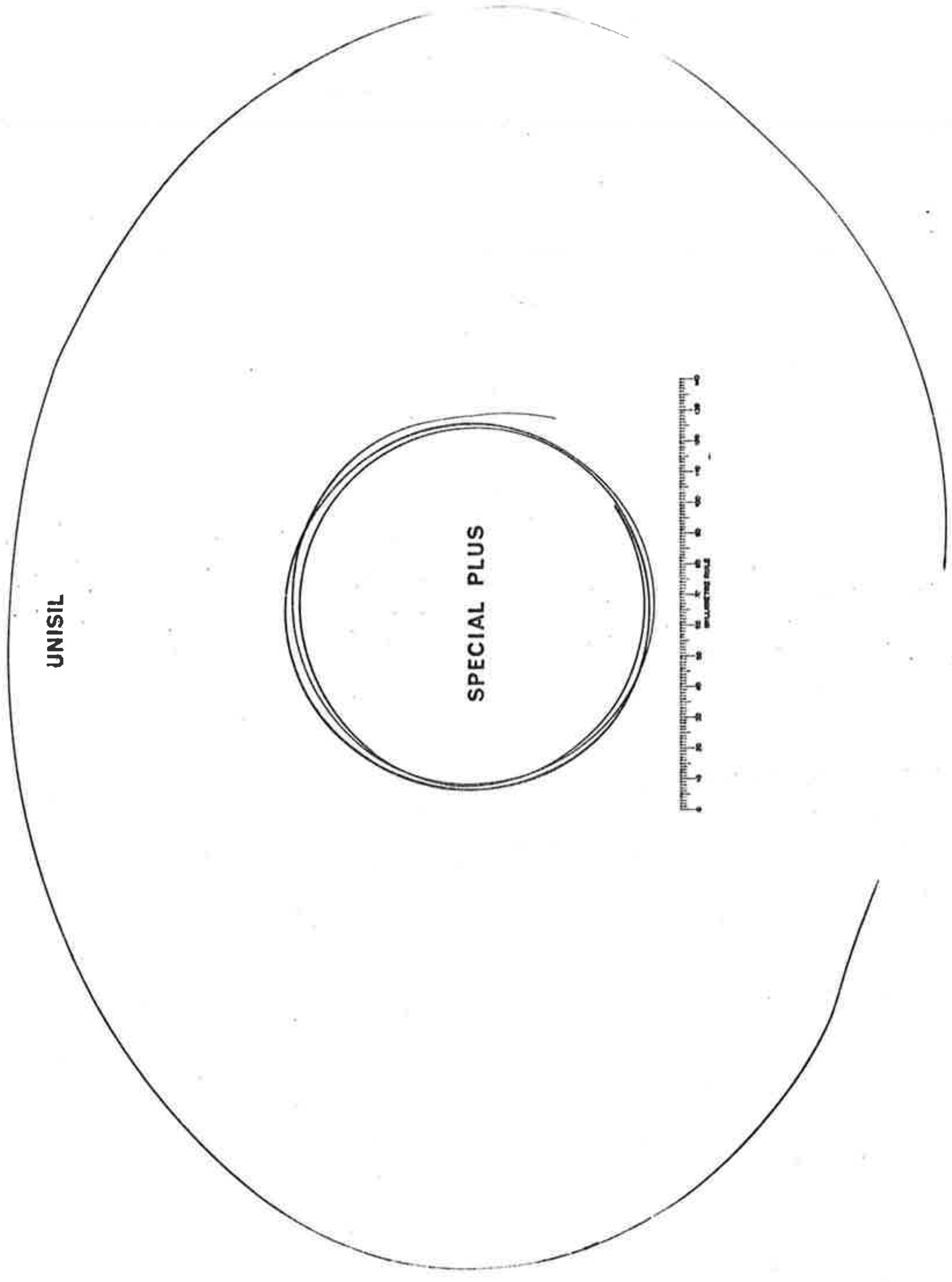
The load was removed from the wires after 16 weeks. Figure 19 shows 160 cm lengths of Special Plus and Unisil immediately after removal from the spool on which they are supplied. A photograph of the two 160 cm lengths after testing appears in Figure 20.

Comparison of these photographs provides a visual demonstration of the markedly differing stress relaxation properties of these two wires. The resistance of Special Plus wire to stress relaxation is demonstrated



Appearance of Wire before long-term Stress Relaxation Test.

Fig.19



Appearance of Wire after long term Stress Relaxation Test.

Fig.20

by the maintenance of its original coil size. Unisil, however, showed a marked increase in the size of the coil shape after the test which indicated that much more stress relaxation occurred in this wire than in Special Plus.

6.3 Hardness Tests

6.3.1 Hardness Values

The mean value and standard deviation of the Vickers Hardness of each of the wires is shown in Table 10. These values were calculated from six hardness determinations on each wire.

TABLE 10

WIRE	VICKERS HARDNESS OF WIRES	
	MEAN $VH_{0.3}$	S.D.
Premium Plus	810	12
Premium	792	12
Special Plus	786	12
Special	680	14
Unisil	768	32
Dentaurum	720	10
Yellow Elgiloy	594	11

6.3.2 Relationship between Hardness and Tensile Properties

The hardness of the orthodontic wires was found to be linearly related to ultimate tensile strength from a plot of $VH_{0.3}$ against U.T.S. Analysis of the experimental results by the 'Method of Least Squares' revealed the relationship to be U.T.S. = 605 x $VH_{0.3}$ - 58,000 p.s.i.

The deviation of the results from the line of best fit was 0.955 which indicated that a very good correlation existed.

A similar analysis showed that the hardness was not linearly related to either proportional limit or 0.1% proof stress.

6.4 Metallographic Observations

The stainless steel wires were examined using the optical metallographic techniques outlined in Chapter 5.6. Photomicrographs of representative structures of the wires are reproduced in Figs. 21-26 at a magnification of 300 X.

All wires have a drawn fibrous structure which arises from the extensive degree of cold work during the drawing procedure. The individual grains of the material have been distorted to such an extent that the grain boundaries cannot be distinguished. Any variation in the degree of cold work through the cross-section of the wires cannot be detected. In this regard, the structure is homogenous from the surface through to the central core. Theoretically the surface of a wire is more severely cold worked than the central area during wire drawing (DIETER, 1961).

The presence of non-metallic inclusions may impair mechanical properties (HONEYCOMBE, 1968). If inclusions are present in these wires, they have been drawn out to such an extent that they cannot be detected.

Significant differences in the structures of the wires cannot be established. As the mechanical properties vary considerably, it appears that the optical metallographic techniques used in this investigation are unlikely to yield information which enables the structure to be correlated with different mechanical properties.

Fig.21 Microstructure of Wilcock Premium Plus Wire

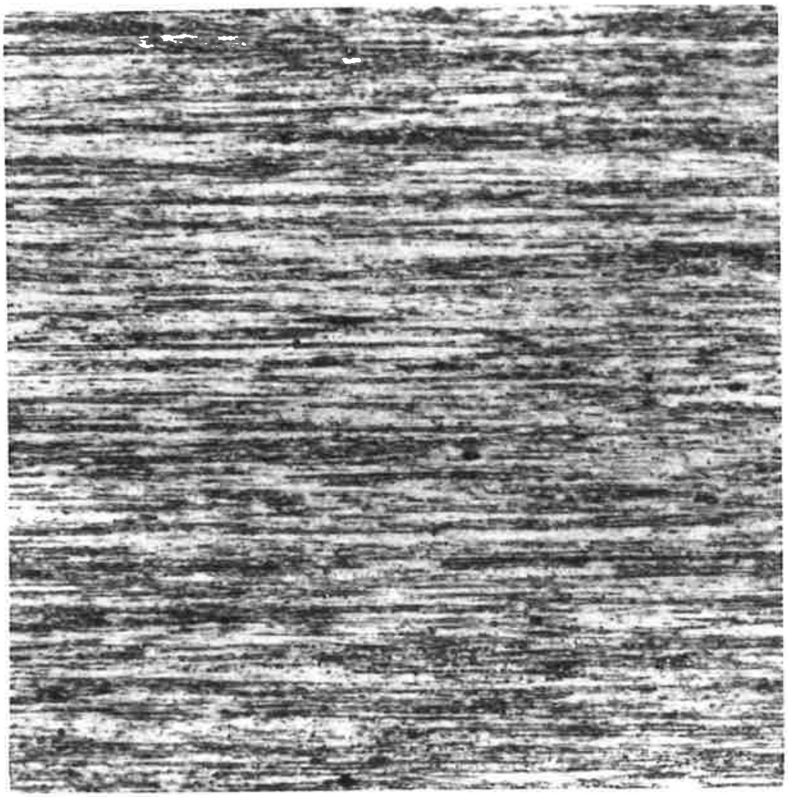


Fig.22 Microstructure of Wilcock Premium Wire

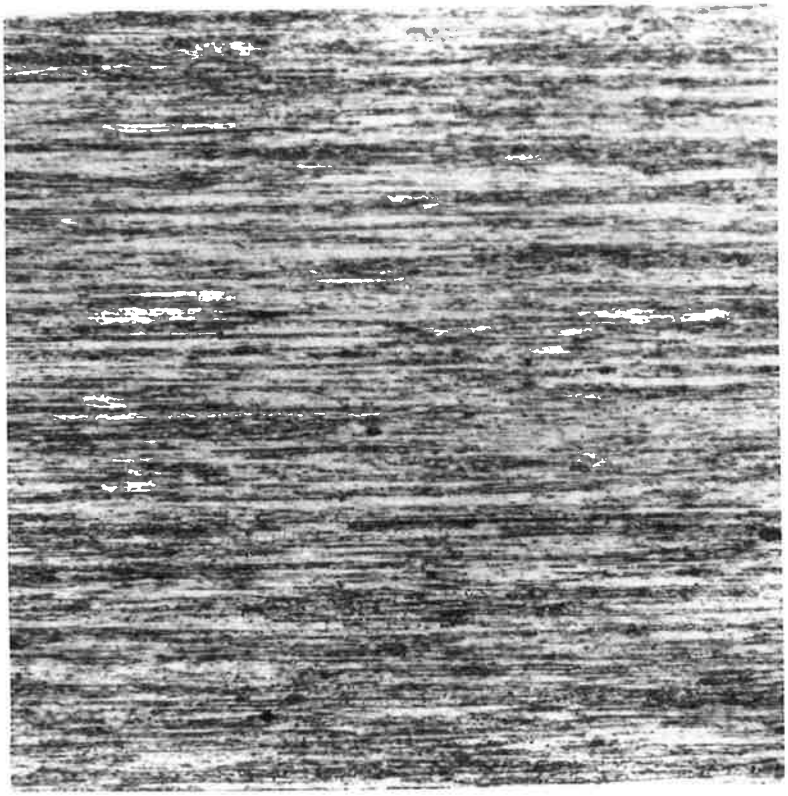


Fig.23 Microstructure of Wilcock Special Plus Wire

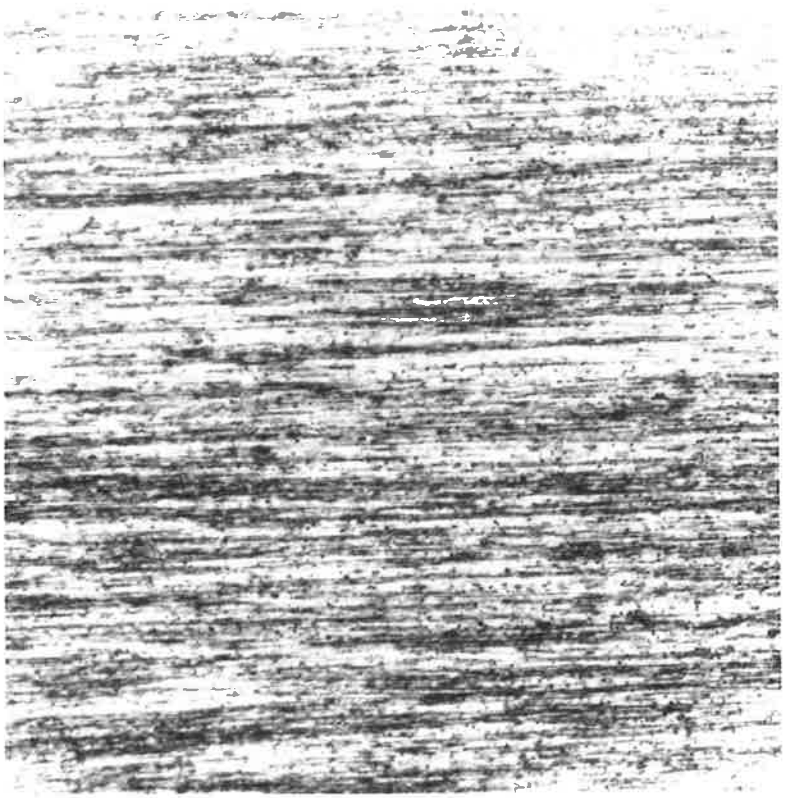


Fig.24 Microstructure of Wilcock Special Wire

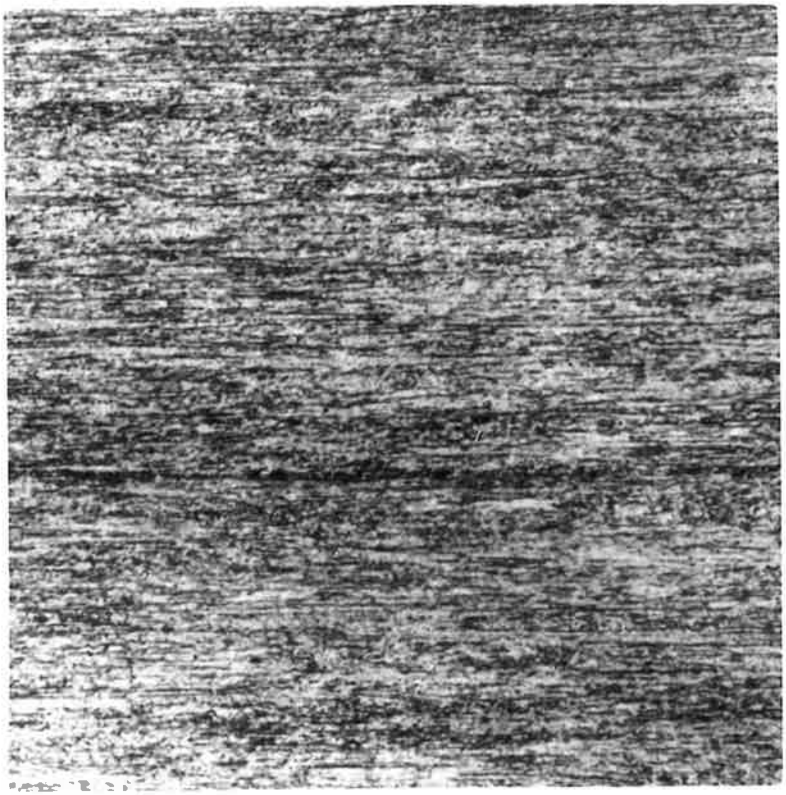


Fig.25 Microstructure of Unisil Wire

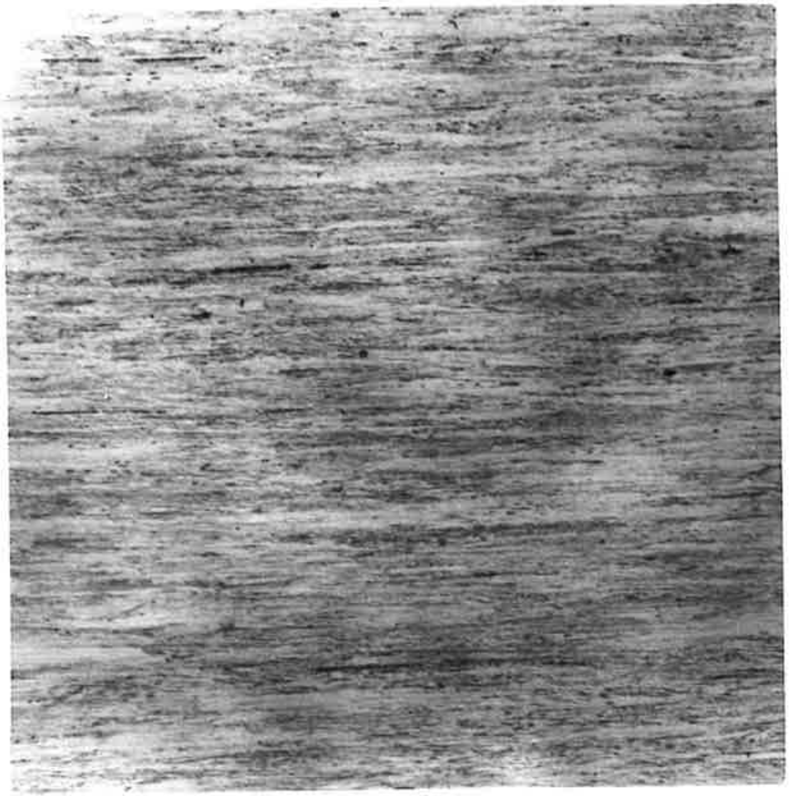
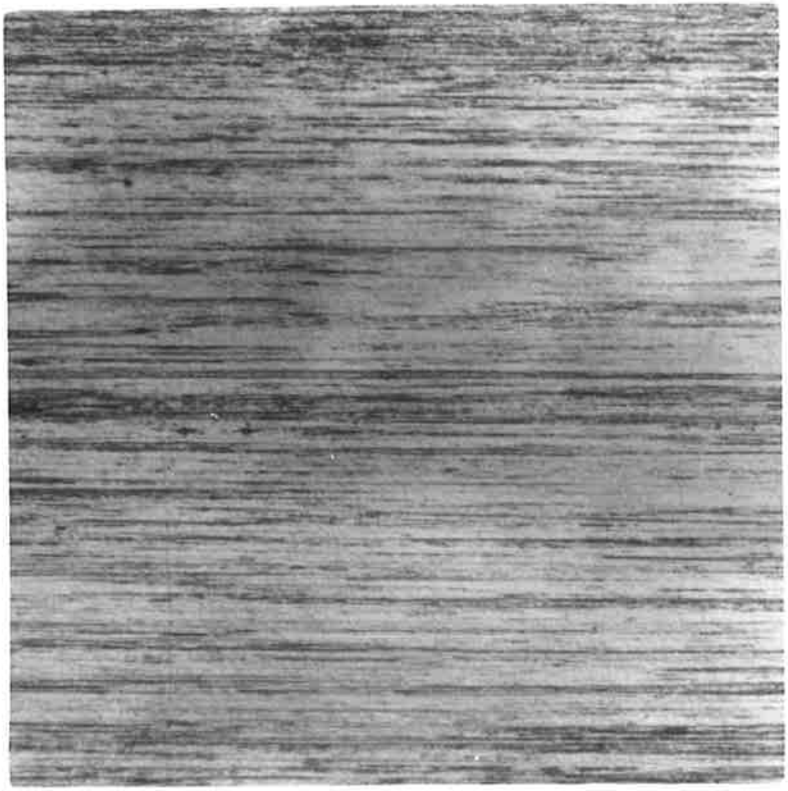


Fig.26 Microstructure of Dentaurum Super Special Spring Hard Wire



7. DISCUSSION

7.1 Tensile Tests

The elastic strength of orthodontic wires is best described by the proportional limit determined from a tensile test (Section 3.6). Consequently, Wilcock Premium Plus and Premium wires had the best elastic properties of the wires tested. No significant differences in proportional limit were found between the other wires (Section 6.1.2). However, MASSON (1969) found that Unisil wire had a significantly higher proportional limit than Special Plus. It is difficult to resolve this discrepancy but it is considered that the apparatus used in the present investigation is more sensitive than that used by MASSON.

The proof stress determinations confirmed the above findings with the exception that Yellow Elgiloy became significantly inferior to the other wires as the level of plastic strain at which the proof stress was determined increased. This means that the strain-hardening rate of Yellow Elgiloy wire decreased more rapidly, after the proportional limit was reached, than the other wires. Therefore, the reliability of proof stress as an indication of proportional limit, and consequently elastic properties, decreases as the plastic strain at which the proof stress is determined increases. However, practical experience demonstrates that at the smaller plastic strain levels e.g. 0.02%, measurement of the proof stress becomes more inaccurate. MASSON (1969) recommended the 0.02% proof stress as a standard, but this author considers that this strain level is too low to offer any great advantage over the proportional limit determination.

Therefore, although it is theoretically desirable to measure a proof stress value for comparison of elastic properties (MASSON, 1969 and TWELFTREE, 1973) this method suffers some disadvantages when wires with different work hardening characteristics are compared. For comparison of the elastic properties of the stainless steel wires in this study, proof stress values at relatively high plastic strains, e.g. 0.1%, would be accurate and reliable measures. However, for accurate comparison of the elastic properties of these wires with Elgiloy wires, the proportional limit must be used because the proof stress values would not equally reflect elastic properties.

The results of this study agree with WILKINSON (1962) and MASSON (1969) who found that the ratio between proportional limit and ultimate tensile strength was not constant (Section 6.1.5). However, it was found that as the ultimate tensile strength increased, the proportional limit increased. This trend is in agreement with the results of NEWMAN (1963).

THE AUSTRALIAN STANDARD T32 and the British Standard for Spring Wire (BRITISH STANDARD 2056, 1953) use ultimate tensile strength as an indication of elastic properties. It is this author's conclusion that this parameter is useful to broadly classify orthodontic wires although it would be desirable to include the proportional limit or a proof stress value in these standards to provide a quantitative basis for comparison.

The moduli of elasticity of the wires were found to vary from 15.0×10^4 MPa (21.5×10^6 p.s.i.) for Wilcock Special to 17.4×10^4 MPa

(24.9×10^6 p.s.i.) for Wilcock Premium Plus. BURSTONE (1961, 1962, 1966, 1969) stated that the elastic modulus should be as low as possible to produce minimal force per unit deflection. WILKINSON (1960), however, said that variations in the elastic modulus could be compensated for by altering the diameter of the wire. The force produced by straining a wire is directly proportional to the modulus of elasticity but proportional to the fourth power of the diameter of the wire (WARE, 1967). Therefore, it is unlikely that the relatively small variations in elastic modulus could be compensated for by changing the diameter of the wire because the range of available sizes is not sufficiently comprehensive.

When an archwire is used to orthodontically move teeth, it is advantageous to use a wire with a low elastic modulus (BURSTONE, 1961, 1962, 1966, 1969). However, when the wire is used to exert a force on a tooth for a long period of time, a high elastic modulus is preferable. This is because the strain required to produce the force is less with a stiffer wire and the application is consequently easier to control. It is of interest to note at this stage that wires with superior stress relaxation properties also had the highest moduli of elasticity (see Section 7.2).

It is this author's opinion that a wire with a high elastic modulus is preferable for the construction of a Stage 1 Begg archwire. Any additional flexibility required for specific purposes, e.g. for alignment of teeth, may be provided by increasing the length of the wire by bending loops into the arch form. However, the clinical significance of the differences in elastic moduli between the wires remains unresolved.

7.2 Stress Relaxation Tests

The conclusions drawn from Section 6.2 were that stress relaxation occurred in orthodontic wires and to a different degree in different wires. However, the short term results could not be accurately extrapolated to a clinically significant time period because they did not appear to conform with simple mechanical analogues.

Stress relaxation could affect the efficiency of the Begg orthodontic appliance which depends on the maintenance of applied forces from an active archwire for periods of up to six months (Section 3.2). Any stress relaxation which resulted in a clinically significant decrease in applied force would adversely affect anchorage control and general efficiency of the appliance.

The results of Section 6.2.2 indicated that over a period of three days Wilcock Premium Plus, Premium and Special Plus showed significantly superior stress relaxation characteristics when compared with the other wires. If this trend was maintained, they would be considered to be preferred for archwire construction.

Since the occurrence of stress relaxation has now been established, future work should be directed towards investigating the clinical significance of the phenomenon, i.e. the magnitude of the decrease in force exerted by the archwire. If stress relaxation is found to be important, methods of quantifying stress relaxation require development.

7.3 Hardness Tests

The hardness of the wires was found to be directly proportional to the ultimate tensile strengths (Section 6.3.2). This finding agrees with the results of WILKINSON (1962), BUSH, TAYLOR and PEYTON (1951) and KEHL (1949). Therefore, hardness could be used to broadly classify wires without necessarily providing accurate data on elastic properties.

The absence of direct proportionality between hardness and either proportional limit or proof stresses (Section 6.3.2) was expected because no direct relationship was found between ultimate tensile strength and these values (Section 6.1.5).

A hardness test could be useful in laboratories where this measurement could be made more conveniently than a tensile strength determination.

7.4 Metallographic Observations

The metallographic techniques employed in this study did not reveal microscopic details of the grossly distorted structures of the orthodontic wires (Section 6.4). This finding supports the conclusions of WILLIAMS and VON FRAUNHOFER (1971) who stated that chemical etching would not reveal the structures of cold worked materials. The author supports these workers in agreeing that advantages in testing and developing orthodontic wires could be gained if microstructures were correlated with mechanical properties.

8. CONCLUSIONS

1. The mechanical property of ultimate tensile strength may be used to qualitatively grade orthodontic wires with respect to their elastic properties.

2. The proportional limit is the only satisfactory measure of elastic properties of a wide range of orthodontic wires.

3. The 0.1% proof stress value may be used to quantitatively compare wires with similar strain-hardening rates, for example, stainless steel wires.

4. The modulus of elasticity is probably only of marginal value in determining elastic properties of orthodontic wires.

5. Wilcock Premium Plus and Premium grade wires have superior elastic properties to the other wires.

6. Wilcock Special and Special Plus, Unisil, Dentaurum Super Special Spring Hard and Yellow Elgiloy wires do not have significantly different tensile elastic properties.

7. Stress relaxation occurs in orthodontic wires and to different degrees in different wires over a three day period.

8. Over a three day period, Wilcock Premium Plus, Premium and Special Plus wires have superior stress relaxation properties when compared with the other wires.

9. Hardness may be used to qualitatively grade orthodontic wires with respect to their elastic properties.

10. Optical metallographic techniques utilizing simple chemical etching procedures are not suitable to examine details of the micro-structure of orthodontic wire.

9. SUGGESTIONS FOR FUTURE INVESTIGATION

1. The clinical significance of the stress relaxation properties of orthodontic wires requires investigation to determine the importance of this phenomenon in wire selection. Initially, the reduction in force exerted by an activated anchorage bend or root tipping spring over a four or six month period should be determined. If this is found to be significant, and different for different wires, the clinical significance should then be investigated by a controlled clinical study. This could be achieved by comparing the effectiveness of root tipping springs constructed from different wires in the same patient.

2. If the differences in stress relaxation properties of different wires are found to be clinically significant, methods of quantifying stress relaxation require development. However, for practical purposes, it would be advantageous to develop a short term test which predicts the long term effects of stress relaxation. The methods used in the present study to measure stress relaxation may prove useful if the accuracy of extrapolation of the results could be established. Alternatively, the rate of relaxation could be increased by conducting the test at high temperatures and extrapolating the results back to body temperature.

3. Investigation of the microstructure of orthodontic wire requires a method of metallurgical examination which will reveal the pertinent details of the grossly distorted structure. It appears that simple etching procedures are not adequate (Section 7.4) and that the development of suitable techniques is required. The electrochemical method used by WILLIAMS and VON FRAUNHOFER (1971) may prove useful.

10. APPENDICES

10.1 Appendix 1

The following theory was used in an attempt to extrapolate the results of Section 5.4. It was assumed that the response of the wire would approximate the behaviour of the Maxwell Model, i.e. when a low load was applied essentially elastic deformation would occur. Once the predetermined level of stress was reached, the strain was held constant for some time. This would permit any viscous elements to flow at a rate determined by the viscosity of the elements. As this occurred, i.e. as the plastic component of the total strain increased, the elastic component of the strain would decrease and consequently, the elastic stress in the wire would decrease. This reduction was recorded as a decrease in load by the load cell.

These assumptions were tested by use of the following theory:

ε = total strain

ε_e = elastic strain

ε_v = viscous strain

E = Modulus of Elasticity

η = Coefficient of Viscosity

σ_o = initial stress at strain ε

σ = stress at time t

t_r = Relaxation Time

$$\varepsilon = \varepsilon_e + \varepsilon_v$$

$\therefore$ $$\frac{d\varepsilon}{dt} = \frac{d\varepsilon_e}{dt} + \frac{d\varepsilon_v}{dt} = 0 \text{ as total strain constant}\ldots\ldots(1)$$

As $\sigma = E\varepsilon_e$ (Hooke's Law)

$\therefore$ $$\varepsilon_e = \frac{\sigma}{E}$$

$\therefore$ $$\frac{d\varepsilon_e}{dt} = \frac{1}{E}\cdot\frac{d\sigma}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

As $\sigma = \eta \dfrac{d\varepsilon_v}{dt}$ (Section 2.2.5),

$$\frac{d\varepsilon_v}{dt} = \frac{\sigma}{\eta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Substituting equations (2) and (3) in equation (1),

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\cdot\frac{d\sigma}{dt} + \frac{\sigma}{\eta} = 0$$

i.e. $$\frac{1}{E}\cdot\frac{d\sigma}{dt} = -\frac{\sigma}{\eta}$$

$\therefore$ $$\frac{d\sigma}{dt} = -\frac{\sigma . E}{\eta}$$

$\therefore$ $$\frac{d\sigma}{\sigma} = -\frac{E}{\eta}.dt$$

$\therefore$ $$\ell n\,\sigma = -\frac{E}{\eta}.t + k \text{ where k is a constant} \quad \ldots\ldots\ldots(4)$$

At $t = 0$, $\sigma = \sigma_o$ and $k = \ell n\sigma_o$

$\therefore$ $$\ell n\frac{\sigma}{\sigma_o} = -\frac{E}{\eta}.t$$

$\therefore$ $$\frac{\sigma}{\sigma_o} = e^{-\frac{E}{\eta}.t}$$

$$\therefore \quad \sigma = \sigma_o . e^{-\frac{E}{\eta}.t}$$

Relaxation Time, $t_r = \frac{\eta}{E}$ (VAN VLACK 1960)

$$\therefore \quad \sigma = \sigma_o . e^{-\frac{t}{t_r}}$$

$$\therefore \quad \frac{\sigma_o}{\sigma} = e^{\frac{t}{t_r}}$$

$$\therefore \quad \ell n \frac{\sigma_o}{\sigma} = \frac{t}{t_r}$$

i.e. $t_r = \frac{t}{(\ell n\sigma_o - \ell n\sigma)}$ ....(5)

From equation (4), a graph of $\ell n\,\sigma$ against t should produce a straight line if the wire behaved according to the theoretical behaviour of a Maxwell Model. If this relationship was found to exist, the relaxation time of the wire could be calculated from equation (5).

From Fig. 15 it can be seen that after 24 hrs, the graph of ℓn stress against time approximated a straight line. Therefore the stress levels at 24 hrs and 72 hrs could be used to calculate a relaxation time for the wire. The results of these calculations are recorded in Table 11.

TABLE 11

WIRE	RELAXATION TIME (days)
Premium Plus	Not calculable - no decrease in stress between 24 and 72 hrs
Premium	" "
Special Plus	2000
Special	282
Unisil	385
Dentaurum	667
Yellow Elgiloy	556

These relaxation times are not the true relaxation times of the wires because some relaxation had occurred before the wire began to behave according to the predictions of the Maxwell Model. As the rate of this preliminary relaxation was greater than the rate after 24 hrs, the true relaxation times would be considerably shorter than those calculated.

The results, however, correlate with the conclusions drawn in Chapter 6.2.2 in that Premium Plus, Premium and Special Plus wires are superior in stress relaxation resistance compared with the other wires.

The clinical significance of stress relaxation in orthodontic wires needs to be established.

10.2 Appendix 2

Samples of Wilcock Special Plus were vacuum annealed and metallographically examined to further investigate the metallurgical structure of orthodontic wire.

Initially the samples were annealed at 700°C for 4 hrs. The structure resulting from this heat treatment is shown in Fig. 27. It is seen that some recrystallization had occurred although the grains can not be resolved. Consequently, samples were annealed at 900°C for 4 hrs with the resultant structure shown in Fig. 28. Although grain growth had occurred, further resolution of the structure would be desirable. Therefore, samples were annealed at 1000°C for 4 hrs. The result after this anneal is shown in Fig. 29.

The individual grains can be readily identified. The photomicrograph shows that there are no significant amounts of impurities or inclusions in the structure.

The distribution of particles is affected by the annealing process (compare Figs. 27, 28, and 29) and so they probably represent a second phase and not impurities. The fibrous appearance of the cold-worked wire may be due to elongation of these particles.

Fig.27 Microstructure of Wilcock Special Plus Wire annealed at 700°C

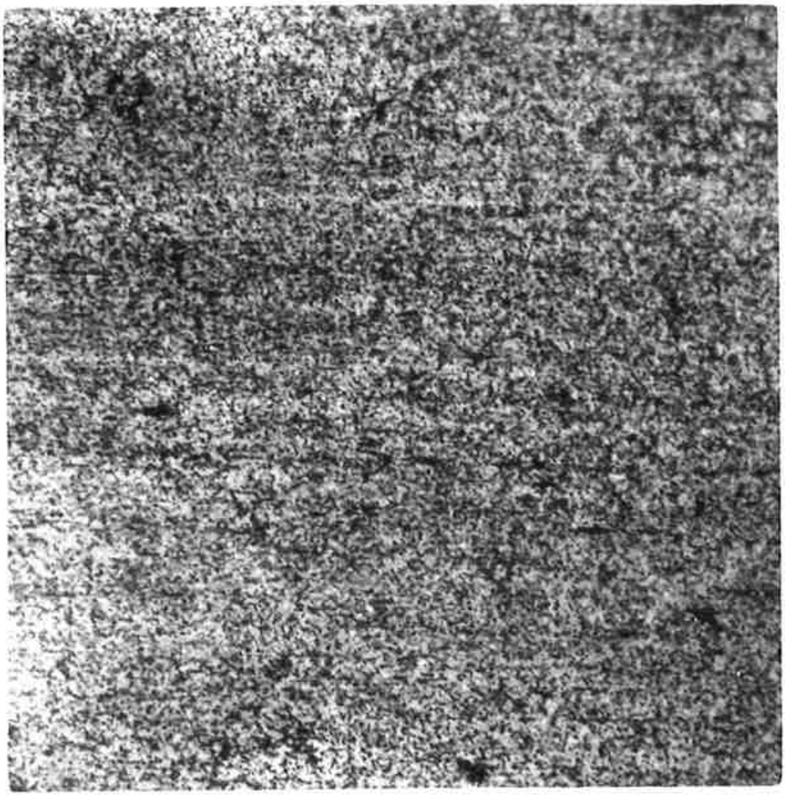


Fig.28 Microstructure of Wilcock Special Plus Wire annealed at 900°C

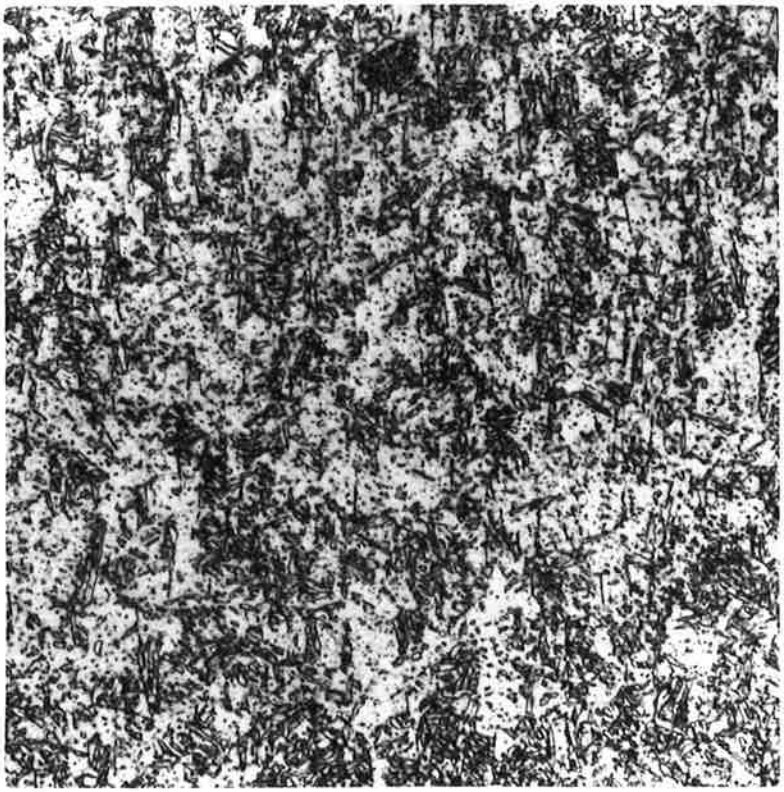
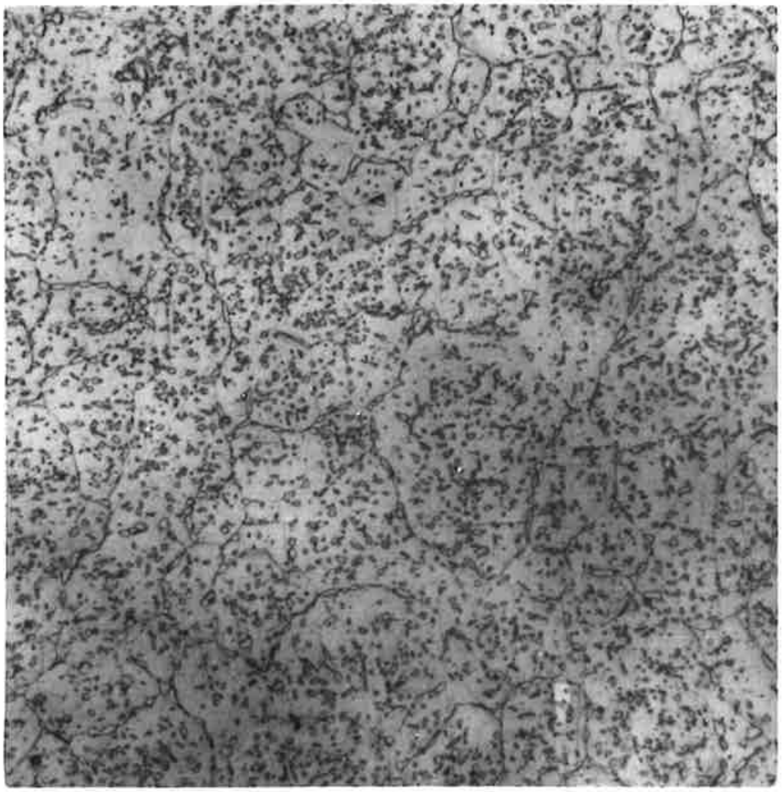


Fig.29 Microstructure of Wilcock Special Plus Wire annealed at $1000^{\circ}C$



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