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AN EVALUATION OF .016 INCH ORTHODONTIC LIGHT WIRES

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A Thesis submitted in partial

requirement for the degree of

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Faculty of Dentistry

University of Sydney

1969

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Ronald James Masson B.D.S.

November, 1969

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INTRODUCTION

The purpose of this project was to evaluate the effectiveness of certain .016 inch diameter orthodontic wires for use in the Australian (Begg) Light Wire Technique.

The wires tested, comprised six proprietary brands of stainless steel wires, and a cobalt nickel alloy wire which had been subjected to heat treatment.

Specifically the wires were:

(1) Wilcock Wire, the complete range.

"Special Plus", "Special", "Regular Plus" and "Regular".

This wire is known in overseas orthodontic circles as "Australian Wire".

(2) Dentaurum Remanit, "Super Spring Hard".

This wire is marketed in the U.S.A. as "Boomerang Wire".

(3) "Unisil".

(4) "Red Elgiloy" (Cobalt Nickel Alloy).

By studying and comparing values of the mechanical properties exhibited by these wires under test, it was aimed at establishing which of these wires were suitable to be used in the construction of archwires for use in Stage 1 and Stage 2 of the Australian (Begg) Light Wire Technique.

The wires chosen for comparison were those which are commonly used by Orthodontists both Australian and American who carry out treatment using the Australian (Begg) Light Wire Technique, or else wires that have been suggested as having a possible use in this technique, by various authorities. Thus for my own guidance and possibly that of others who might read this thesis, was the evaluation of these wires undertaken.

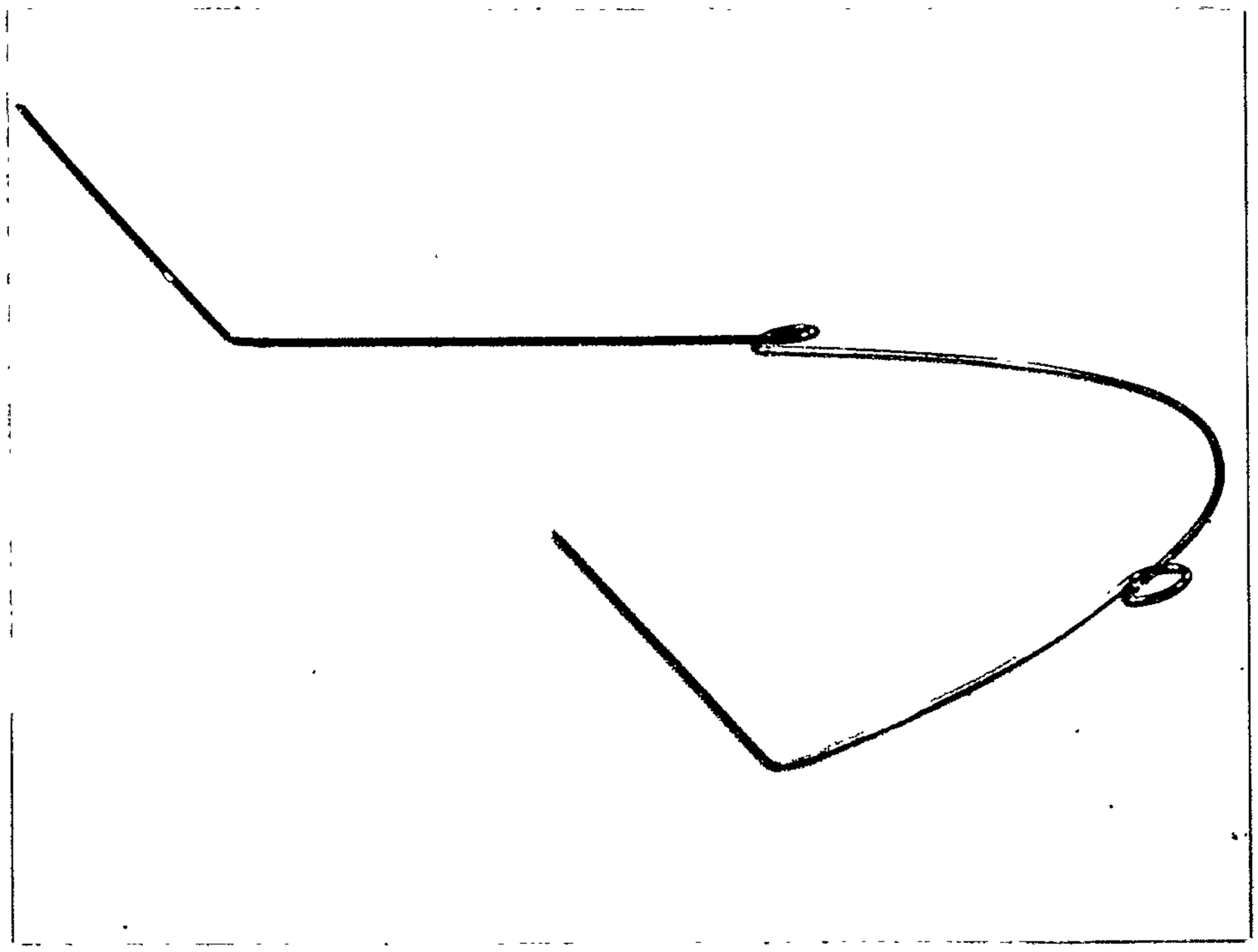


Fig. 1 - A Begg Archwire.

Illustrating anchor and/or bite opening bends and intermaxillary hooks.

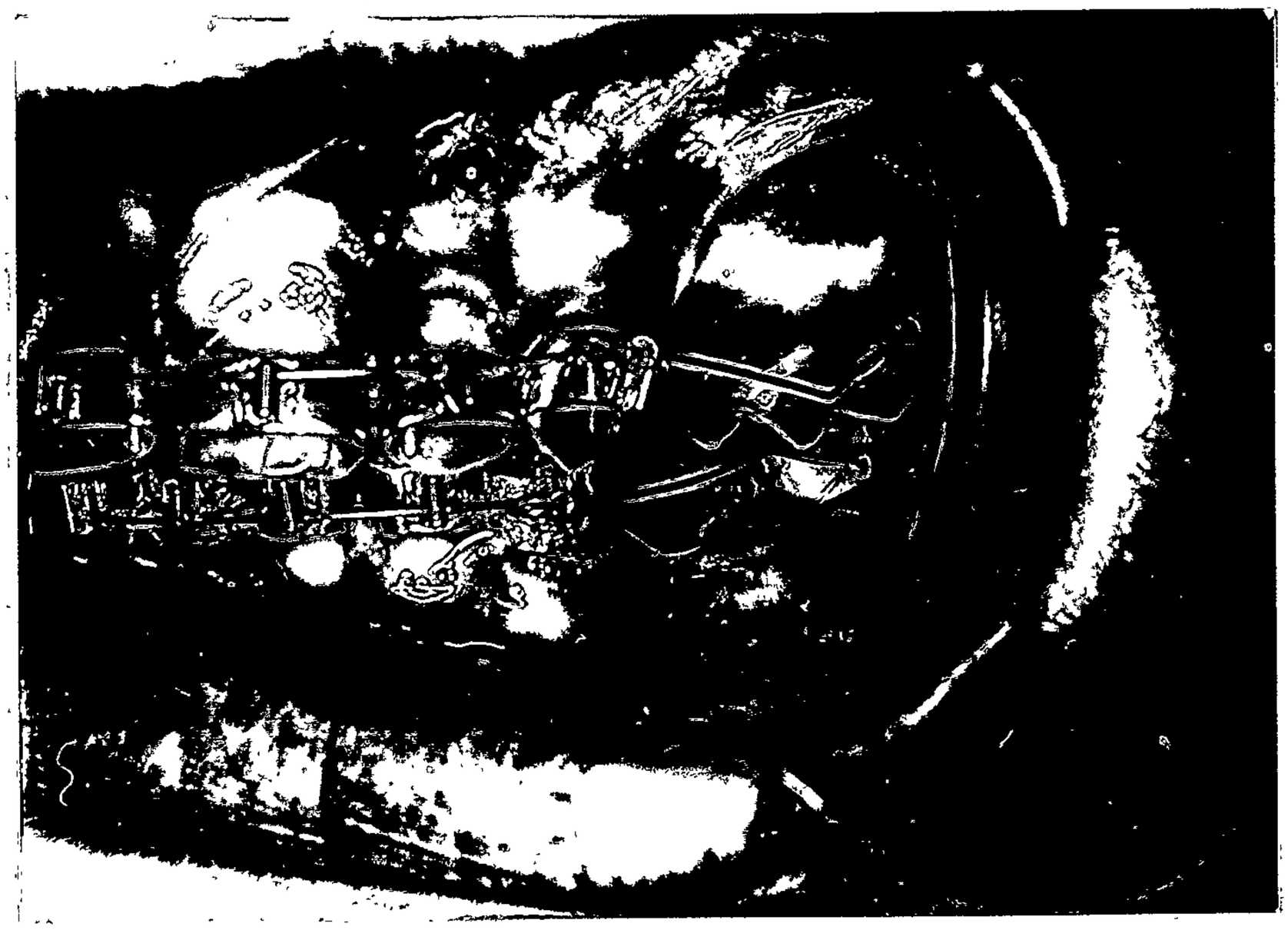


Fig. 2 - Stage 1. Begg Technique showing position of anchor and/or bite opening bends in upper and lower arches.

CHAPTER 1

THE DEVELOPMENT OF ORTHODONTIC ARCHWIRES

Edward Angle had such an outstanding influence on the development of Orthodontics, that it is appropriate to arrange a review of Orthondontic development around this central figure, by dividing the coverage into three sections:

(1) Pre-Angle

(2) Angle

(3) Post-Angle

(1) Pre-Angle

Archwires of various forms have been used in orthodontic therapy since the days of Fauchard's sectional type arch, which he described in his book "The Surgeon Dentist" in 1746[25]. This consisted of a ribbon of metal, either gold or silver, shaped around the buccal outline of the teeth, and perforated for the reception of ligatures of common thread or silk, with which attachment was made to the anchor teeth as well as to the teeth to be moved. This was a rigid archwire and the malplaced teeth were drawn to it by gradually tightening the ligatures. Fauchard's initial idea was carried on and modified and perfected over the years. Schange (1841) (Anderson)[2] gave better anchorage attachments by skeleton cribs attached to the molars.

Harris (1850)[29] employed a modified expansion arch to treat a complete arch. The band of gold was shaped around the full arch in the desired arch form. This shaped arch was then soldered to caps that had been swaged to fit the anchor molar teeth. The archwire was then fitted to the arch and the teeth were attached to it in a similar manner to that used by Fauchard by passing either silk or elastic thread through the perforations in the gold archwire, thus drawing the teeth to the position predetermined by the desired arch form.

In 1854 Thomas Evans (Anderson)[2] came up with the beginnings of the present modern arch when he used horizontal buccal tubes on the molars, to these tubes were attached a threaded device for holding and expanding the archwire.

Magill used cement to attach a platinum band to a tooth in 1871 (Anderson)[2] and by 1879 dental cement was in general use by the dental profession, and with it a better method of attaching bands to teeth.

Farrar (1888)[24] made reference to cement, when commenting on Dr. Patrick's "Bow Spring Arch" (1883) he noted that the appliance was attached to the anchor molar teeth by cementing the tooth ferules to the teeth with "phosphate of zinc cement".

(2) Angle

This brings us to the era of Angle. Weinberg, writing in Anderson's "Practical Orthodontics", stated: "To Edward H. Angle, Orthodontics owes the renewed impetus instilled into our science."

In his book "Malocclusions of the Teeth" 1907[4] Angle described how he, in 1888 designed and constructed his "A" appliance, "it consisted of a delicate round bar of metal bent to the shape of an ideal arch". The ends of this archwire were supported by loosely telescoping tubes and it was attached to the anteriors by plain bands.

Angle progressed with various new ideas and innovations through his "E" Expansion arch 1903, Pin and Tube appliance 1912, Ribbon arch 1916, and culminating in 1926 with his Edgewise Technique (Anderson)[2].

True Edgewise therapy according to Dr. Angle was a full banding technique utilising slotted rectangular brackets attached to bands and cemented to the teeth. Into these bracket slots was placed a rigidly fitting rectangular gold platinum wire and this was tied into the brackets by means of ligature wire. Angle stated in 1928[5]: "It must always be remembered, in the use of these arches that since their attachments within the brackets, that is, between the walls of the brackets is rigid, the amount and directions of movements of teeth individually and collectively

will correspond wholly and completely to the bends that are made in them." Thus at all times teeth were rigidly held and controlled; his aim was bodily movement of the teeth.

(3) Post Angle

This period of time up till the present can be sub-divided into:

(a) Modifications to the Edgewise Technique

(b) The development of "Light Wire" Techniques.

(a) Modifications to the Edgewise Technique

Tweed (1941)[55] wrote of his modification of the procedure and treatment with Edgewise Technique. In the initial stages of treatment he used round stainless steel wire. If no spacing was present in the arch, he used .016 inch wire with tip back bends, but if spacing were present then he used .018 or .020 inch wire with stops 1/8 inch anterior to the molar sheath and the arch was tied to the molar sheath in such a way as to close the spaces. Whereas Angle used rectangular archwire from the start, Tweed had found the advantages of using a loosely fitting round archwire in so far as it allowed greater tipping of malplaced teeth during the stage of initial alignment, this would not be possible with rectangular wire. It also allowed for easier engagement of the archwire in the bracket.

(b) The development of "Light Wire" Techniques

Even during the time when Angle was exerting a great influence on

Orthodontics, there were already men who were concerned about the heavy forces exerted by the appliances then in use.

Robinson[45] in 1918 stated: "Nine or ten years ago, a number of men apparently about the same time reached the conclusion that they were using too much force, and began reducing the size of the wire used for the expansion arches." He also related in the same article his development of his appliance "A Looped Arch and Its Attachments" which he had presented in 1915[44] (see Figures 3 and 4), the archwires were .018 inch tungsten wire and .020 inch platinum-gold wire. Referring to Angle's Ribbon Arch which Angle had presented in 1916, he claimed that Angle had but modified his (Robinson's) "Looped Arch and Its Attachments".

Again Robinson (1918)[45] noted an important feature of the use of lighter wire, "the smaller wire also performs its work without the soreness which attends the use of the larger appliance, and this factor does not receive the attention which it deserves at the hands of most orthodontists". Robinson described his appliance as being "a non-rigid arch made to the size and shape of the true dental arch, but of a material so flexible that it can readily spring to the size and shape of the arch as it is in malocclusion, and so resilient that it will, when properly locked to the teeth carry them to their proper places". This appliance also required very few adjustments as opposed to other appliances of the day. In the discussion which followed the presentation of this paper by

Fig. 3.

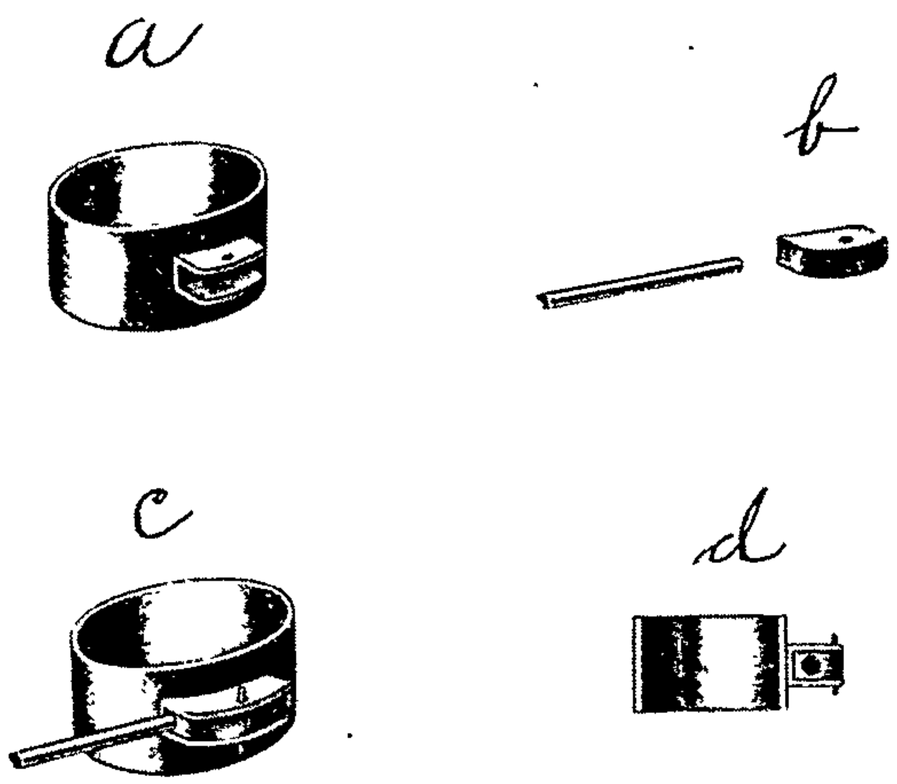


Fig. 4.

Figs. 3 and 4 - Robinson's Looped Arch and Its Attachments. Reprinted from original Int.J.Orthod.1915.

Robinson to The American Society of Orthodontists in 1917 a Dr. Flint commented: "In using a small wire, if you are not watchful of its force, you will get into trouble handling it." Such a statement could be made today some 40 years later at a meeting of any Begg group.

Thus although a great deal of prominence has been given Robinson in this review, he has justly, to my mind, deserved it, as he appears to have initiated a move to lighter wires and also to have appreciated the benefits derived from the greater flexibility and lighter forces, long before the time of Johnson, Atkinson, Jarabak or Begg.

Johnson (1938)[33] first utilised light wire in 1931 when he developed his Twin Wire Technique. This appliance used two .010 inch round wires. The advantage of this appliance was that as the thickness of the wire used was .010 inch, the wire was very flexible, this allowed a light continuous force to be applied over a long range of tooth movements. Due to the light forces delivered by this appliance, its greatest use is found in late mixed and early permanent dentition treatment.

Atkinson (1937)[8] wrote "There is a definite trend in modern orthodontic strategy toward the reduction, refining and control of force used to move teeth".

He also expressed his thoughts on the Edgewise Arch Technique: "When a heavy wire is sprung into a close fitting bracket, the

tooth and periodontium are subject to terrific initial force, which is repeated with each adjustment of the arch wire." Continuing he compared this to the effect of light wires: "Small resilient wires do not cause this initial jolt to the periodontium; the application of the force is gentler and more continuous and not so quickly spent."

Atkinson's Universal Appliance made use of these light wires, especially in the early stages of treatment of a badly crowded case. In such a case he advocated the use of .008 or .010 inch wires initially. Later in treatment he would insert a .012 or .015 inch round wire in the gingival slot and a heavier .010 inch or .015X.028 inch rectangular wire occlusally.

Following on after Johnson and Atkinson came Jarabak and Begg. It is quite immaterial to this discussion who came first. For the sake of convenience, however, the Jarabak Technique will firstly be dealt with. Jarabak[32] first introduced his technique in 1963. It was a light wire appliance. The wire used to construct the archwires was .016 inch diameter round wire. In the initial stage of treatment the arch wires consisted of a complex helical loop system. The thought behind this, was the application of the principle that the longer the length of wire the less will be the initial force, but the decrease in force per millimetre of distance moved would be less than a plain looped arch. ,

Jarabak used Edgewise brackets, mainly the twin or siamese type and tubes on the molar teeth as his method of attachment for the arch wires. The wire used was .016 inch "Green Elgiloy", this would make the fabrication of his arch wires somewhat easier. The difficulty in fabrication lay in the bending of so many helical loops in one arch wire. These loops were referred to as vertical, horizontal or transverse. The vertical loops could be made either to open or close spaces in an antero-posterior direction, the horizontal operated in a vertical direction, while the transverse loops moved teeth medio-laterally. He used triangular elastics to elongate his molars in deep bite cases. He also used high-pull headgear in difficult class II cases.

Begg in his original article published in 1954 wrote of his "technique for controlled universal tooth movement by the use of round heat treated .018 inch diameter stainless steel wire".

As this project has to do with the Begg Technique, it would seem appropriate to explain the technique, its development and its principles more fully. This will be done in the next chapter.

CHAPTER 2

THE BEGG LIGHT WIRE TECHNIQUE

This technique has been referred to in the introduction as The Australian (Begg) Light Wire Technique. This was to avoid any possible confusion as to the specific technique to be investigated. Whereas in Australia Dr. Begg's technique is associated with his name, and referred to as the Begg Light Wire Technique, outside of Australia the technique is associated with its country of origin and thus spoken of as the Australian Light Wire Technique. Therefore it was decided to use the composite title. For the same reason, the wire known in Australia as Wilcock wire was referred to by the name commonly given to it outside Australia, due to the association of its use with the Australian Light Wire Technique, namely, Australian Wire.

Development of the Begg Light Wire Technique.

Dr. Begg trained under Dr. Angle, and was no doubt greatly influenced by him. Thus, when he first introduced his technique in 1954[11], and described it as "A technique for controlled universal tooth movement by the use of round heat treated .018 inch diameter stainless steel wire", there was reason for him to compare the functioning of his technique with the work of Angle. This he did when he noted that the mechanism of his technique had

similar principles to the pin and tube appliance, giving controlled tooth movement in three planes of space, which is even simpler to operate than the Edgewise Arch mechanism".

In his original article he made further reference to his use of stainless steel wire as opposed to Angle's use of gold platinum wire for archwire construction. He stressed that in extraction cases the properties of this thin hardened stainless steel archwire make it superior in many aspects for such treatments. He stated: "Gold platinum is susceptible to distortion by mastication where it spans extraction spaces, but stainless steel is seldom affected in this way." He also commented of Dr. Angle "His appliances, the Pin-tube, Ribbon arch and Edgewise arch mechanisms were particularly adapted in both size and shape for exploitation of the physical properties of the gold platinum wire, as this at the time was the best available metal for archwires". This statement could also be made of Dr. Begg and his technique. It has been adapted to the use of highly resilient stainless steel wire, as in his 1954 article in "The Americal Journal of Orthodontics" he explained his light wire technique using .018 inch wire and his molar tubes soldered obliquely to the molar bands to tip the molars distally. With the development of high tensile .016 stainless steel round wire he now advocated the use of this wire[13]. Also he had placed the tubes horizontally on the

molars and incorporated the anchor or bite opening bend 5 mms. anterior to the molar tube.

Thus we see that with the development of better stainless steel wire with "better" properties than before, an even lighter wire will give the desired results.

It could be noted that some people have been confused by the change from .018 inch to .016 inch diameter wire; e.g. Mahler and Goodwin (1967)[36], in a study on the forces delivered by "light wires" found that all the wires tested produced a force in excess of that most satisfactory for tooth movement. However, they had made the mistake of assuming that light wire was .018 inch instead of .016 inch[37].

Principal Features of Technique[12]

The Begg Light Wire Technique is bio-mechanical in its operation. It utilizes the combination of force derived from the .016 archwires and light continuous elastic force to obtain the required tooth movement.

There are three essential features of this technique:

(1) Light .016 inch highly resilient heat treated stainless steel archwires in which are incorporated "bite opening" and/or "anchor" bends are used to open the bite and also hold the anchor molar teeth in position. Into these archwires in the vicinity of the canines, hooks or loops are bent for attachment of inter-maxillary elastics.

In the cases where crowding is present it is also necessary to incorporate expansion loops into the archwire.

(2) The archwire when placed and pinned in the modified ribbon arch brackets is only loosely fitting. This is to allow for the application of the third feature.

(3) The utilisation of light continuous elastic forces (60-70 gms.) to tip the teeth into the desired position with little binding or friction of the archwires. The teeth are later uprighted from this position. As opposed to this we have the Edgewise Arch Technique in which the teeth are rigidly held and heavy forces are used to move the teeth bodily.

Treatment Procedures.

The treatment with the Begg Technique is divided into three distinct stages and each stage must be fully completed before moving into the next stage of treatment.

Stage 1

Use is made of .016 inch archwires with "bite opening" and/or "anchor" bends and inter-maxillary elastics in this stage of treatment to:

(a) Open the bite

(b) Get the anterior teeth back edge-to-edge

(c) Unravel any crowded teeth

(d) Close spaces between teeth

(e) Correct rotations

(f) Bring into occlusion any unerupted teeth

(g) Correct crossbites

(h) Correct molar relationships.

Stage 2

Applies most often in extraction cases. The use of .016 archwire with "bite opening" and/or "anchor" bends and inter-maxillary elastics to hold the bite edge-to-edge is continued. But to these are added four intra-maxillary elastics, one in each quadrant from anchor molar to canine hook. The purpose of these elastics is to achieve the sole purpose of Stage 2.

(a) Closure of the extraction spaces.

Stage 3

In this stage heavier archwire are used. The upper archwire is either .020 inch or .022 inch and the lower usually .018 inch. Also there are additional auxillaries, uprighting springs and a torquing arch. The inter-maxillary elastics are continued.

(a) Torque the roots of the anterior teeth

(b) Upright all necessary teeth till axial inclination correct

(c) Hold anterior teeth edge-to-edge.

Even the critics of the Begg Light Wire Technique must admit how

effective is this therapy in the treatment of cases with deep overbite and the Class 2 Div. 1 case with an immense overjet and often associated deep overbite. The success in opening up these cases lies in the incorporation of the "bite opening" or "anchor" bends in these archwires. With further reference to the "anchor" or "bite opening" bend, some people still refer to it as the "tip back" bend, this is a carry over from the Edgewise days (c.f. Tweed 1941). Begg prefers "anchor" or "bite opening" bend, as these are the functions it performs. The bend is placed in the archwire 5 mms. mesial to the molar tube and at such an angle, that when the archwire is placed in the molar tubes the anterior bow of the archwire rests in the labial sulcus bearing slightly on the tissues. This angle varies from about 50° to 70°.

The success or failure of Stage 1 of the Begg treatment, indeed the whole treatment, lies in the proper functioning of the "anchor" or "bite opening" bends at each end of the archwire. Unless the bite can be opened rapidly, we cannot bring the anterior teeth back to the edge-to-edge position by the use of inter-maxillary elastics. This position is essential for completion of Stage 1 of treatment and must continue to be held through Stages 2 and 3 of treatment. Failure to obtain edge-to-edge relationship in Stage 1 and 2 could lead to a less than satisfying result in Stage 3 if not a disaster, and possibility of further treatment.

Cause of failure of treatment.

Lack of success in Stage 1 of the Begg Treatment can be attributed to two factors, as they affect the anterior teeth adjusting to an edge-to-edge position:

(1) Failure of the bite to open

(2) Failure of the teeth to tip distally.

This is the accepted sequence in which to list these two important factors as it is necessary to firstly open the bite before the teeth can move distally or lingually.

However Factor (2) will firstly be discussed briefly to allow for a fuller discussion of Factor (1) with which this project was vitally concerned.

Factor (2) can be attributed to two causes assuming that the bite has opened satisfactorily:

(a) Incorrect choice of elastics

(b) Lack of patient co-operation.

(a) Incorrect choice of elastics. A force of two ounces is all that is required to move the teeth distally. If too heavy a force is used the anterior teeth will remain unmoved and all that will be achieved is that anchorage will be lost (Storey and Smith)[53,54].

(b) Assuming that correct elastics have been chosen the next cause of failure is lack of patient co-operation, that is failure to wear the elastics twenty four hours per day.

Thus it can be seen Factor (2) Cause (a) that choice of elastic force used has a great bearing on the outcome of Stage 1. Yu(1968)[66] has shown great variations in the various elastics available and in their deterioration in the oral cavity relating these factors to subsequent influence on result of treatment. With the use of the table supplied with some of the better elastics, the distance from the upper canine to lower anchor molar can be measured and from the table, elastic which will deliver the necessary two ounces force over the measured distance can be chosen.

Factor (2) Cause (b). Lack of patient co-operation in the wearing of elastics can be quickly identified by the orthodontist as both anchor and anterior teeth will be immobile, and appropriate patient instruction undertaken.

Factor (1) Failure of the bite to open, can be attributed to two causes also:

(a) Too small an angle for the bite opening bend

(b) Loss of bite opening or anchor bend.

Factor (1) Cause (a). The requirements of the bite opening or anchor bend were given earlier. Namely they were that the bend be 5 mms. mesial to the molar tube and that when archwire was placed in the molar tubes the anterior bow should bear slightly on the tissues of the buccal sulcus.

It is Factor (1) Cause (b) Loss of bite opening or anchor bend, which has caused this project to be undertaken.

The bite opening or anchor bend can be reduced or lost in either of two ways:

Firstly: Loss of the actual angulation of the bend itself.

Secondly: Loss of the effectiveness of the bend due to distortion of the wire across space of the wire span on either side of the bend.

In extraction cases there appears a greater possibility that this could occur, as the wire in the vicinity of the extraction space, is vulnerable to distortion during mastication, due to the impaction of food in and across the extraction space.

Both loss of actual bend angulation and loss of the effectiveness of the bend can in many cases be attributed to the poor choice of wire by the orthodontist. Begg insists that a highly resilient wire be used, but has never given any actual figures as regards to properties of a suitable wire or what the upper and lower limits might be. He himself puts great faith in the "Special Plus" wire produced by A.J. Wilcock of Victoria[13].

It is the aim of this project to compare .016 inch diameter wires commonly used both in Australia and America by testing their various mechanical properties. Especially of importance is the proportional limit of these wires.

The Standards Association of Australia[9] quotes only the ultimate tensile strength (U.T.S.) in the specifications for an acceptable orthodontic wire. Earlier work by Wilkinson (1962)[64] had shown that there is great variations in the ratio of proportional limit to U.T.S. for various wires. Therefore, in choosing an acceptable wire for the Begg technique the quoting of the U.T.S. by the manufacturer is of little help to the orthodontist. Far more could be gained if either the proportional limit of the wire itself were given or else the percentage ratio of proportional limit to U.T.S. were quoted by the manufacturer, or, as will be discussed later, the proof stress.

CHAPTER 3

PREVIOUS COMPARISONS OF ARCHWIRE MATERIALS

One of the first persons to attempt to make a comparison of the properties of orthodontic wires was a metallurgist named Williams[65]. He predicted in 1923 that more time must be devoted to the study of wire for orthodontic use and the physical properties of these wires.

He used piano wire as a standard and compared various gold wires to it. Also he realised that there are certain desirable properties required of an orthodontic wire and he attempted to express these figures as stress and strain.

Brumfield (1930)[18] wrote of the use of orthodontic appliances and of gold and other materials available for their construction. He listed the properties of a good orthodontic wire as strength, stiffness, and lightness or thinness of wire. He also wrote of the possibility of evaluating an appliance of which the effectiveness was known against that of another untried appliance of a different material or alloy.

Precious Metal and Stainless Steel

From about the time in 1932 when De Coster[20] wrote of having used stainless steel in orthodontic appliances since 1924, many comparisons have been made between precious metal and stainless steel for orthodontic purposes.

Friel (1933)[26] wrote of the advantages and disadvantages of stainless steel as opposed to gold. It is interesting to note that Friel quoted the price of one pound of stainless steel wire was from 4s.6d. to 8s.6d. as opposed to £145 for a similar weight of gold wire. This cost factor must have had a great bearing on the initial introduction of stainless steel. He also commented on the greater tensile strength and toughness of the material compared to gold. One of the greatest drawbacks to stainless steel at the time was the difficulty of soldering it. Friel helped overcome this problem when with others in Europe he applied the principle of electric resistance welding to the joining of stainless steel.

Angell (1950)[3] compared 18-8 stainless steel with platinised gold wire using tensile and bend tests for orthodontic wires and springs. He concluded that gold alloy wires would serve orthodontists for arches and springs better than the best stainless steel.

Again in 1953 Steiner[52] compared the physical properties of both precious metal and stainless steel and while both had advantages for use in orthodontic work he considered precious metal to be the most suitable.

Up till this time the appliances mainly in use had been rigid-type fixed appliances to which auxiliaries were attached or the full banding Edgewise Arch Technique. All these appliances would function admirably using gold wire. Especially was this true of appliances which had to be soldered.

Various Stainless Steels and Cobalt Nickel Alloy

With the broadening of the use of stainless steel, we come in the 60's to the era of comparisons of one grade of stainless steel with another or cobalt chromium nickel ("Elgiloy") wire.

The range of stainless steel available for orthodontic use are known in the U.S.A. as grades 302, 304, 316, which are 18-8 stainless steels. Also available are 17-7 and 15-5 precipitation-hardening (PH) stainless steel.

Billberg (1962)[14] examined the mechanical properties of 18-8 stainless steel then available in Sweden for orthodontic use. He carried standardised tensile and bending tests on the chosen wires as a method of comparison. Billberg quoted 90 per cent as the ratio of proportional limit to U.T.S. as the ideal for a high tensile wire.

Wilkinson (1962)[64] carried out comparative work on various small diameter .016 stainless steel wires. Especially was he concerned with the proportional limit to tensile strength ratio. From his testing he obtained figures which showed that for the best high tensile wire tested the ratio of proportional limit to the tensile strength was 59 per cent and dropped to as low as 36 per cent for the wire with the lowest tensile strength tested.

Delgado and Anderson (1963)[21] compared stainless steel wires of varying diameters from 1.00 mm. down to 0.25 mm. Only three wires

of 0.40 mm. were tested; they were a hard drawn and a high tensile from C.K. Smith Ltd. (previously Temco) and a super hard wire from the Stainless Steel Wire Co., Sheffield. Again these workers were concerned with the ratio of proportional limit to tensile strength. They noted also the difficulty of gripping the wires and their subsequent findings of up to 82 per cent for the ratio of proportional limit to tensile strength may have been affected by this problem.

The percentage figures quoted by Delgado and Anderson compare favourably with the figure from Billberg which gives 90 per cent as the ideal ratio for a high tensile wire, but is far above those figures of Wilkinson which ranged from 59 to 36 per cent. The wires although from different manufacturers had somewhat similar tensile strengths. Thus these findings make an accurate and confirmed statement on the ratio of proportional limit to tensile strength difficult to arrive at.

Newman (1963)[41] reported on a comparison of .016 inch round wires. He tested "Australian Wire", 18-8 American stainless steel wire, unbalanced semi-austenitic stainless steel wire and chrome cobalt wire. Newman used an Instron machine for his mechanical testing. He found that the proportional limit of heat treated chrome cobalt alloy wire was slightly higher than "Australian Wire", but gave no figures for the proportional limit of the semi-austenitic wire.

However, he stated that the tensile strength of the semi-austenitic wire was 425,000 pounds per square inch whereas "Australian Wire" was 350,000 to 375,000. He also reported that all wires tested were suitable for use in the Begg technique.

Craig et al (1965)[19] carried out comparative tests on 17-7 precipitation hardenable stainless steel, 18-8 stainless steel and cobalt chromium nickel ("Elgiloy") wires. The 18-8 wires tested were ones commonly used in America, namely, Uniteck and Truchrome. From the point of view of the Begg technique it is of interest that they reported that the properties of 17-7 precipitation hardenable stainless steel in its cold-worked martensitic condition, were comparable with those of 18-8 stainless steel and "Elgiloy". But the yield strength of 17-7 precipitation hardenable stainless steel was superior to any other wire tested and that after the precipitation hardenable stainless steel had undergone precipitation hardening treatment for one hour at 900°F the strength properties increased markedly in comparison with the other materials tested. Yield strength was quoted at 315,000 p.s.i. and tensile strength at 355,000 p.s.i., which gives a ratio of yield strength to tensile strength of nearly 90 per cent. There is, however, a decrease in ductility.

Craig et al also stated it could be used in the work hardened martensitic form followed by heat treatment or even in the

precipitation hardened condition if only limited forming operations are to be carried out on the wire.

Mahler and Goodwin (1967)[36] compared the elastic deformation force ratio and the elastic force limit of stainless steel and cobalt chromium orthodontic wires of small diameter and their application to the 'light wire technique . The wires from different manufacturers were bent into loops of various configurations with pliers. They concluded that of the types, designs and conditions tested, all produced elastic force limits in excess of that thought to be necessary for light wire application.

In their tables of results, Mahler and Goodwin gave no indication of the diameters of the wires tested. On writing to the authors it was found that the wire tested was .018 inch diameter. Thus their findings had no possible bearing on the Begg light wire technique as the wire now used is of .016 inch diameter. As stated earlier the authors may have been misled by Begg's original article in 1954 in which he spoke of having used .018 inch diameter wire.

Howe et al (1968)[30] compared the effects of stress relief heat treatment on grades 302 and 316 austenitic stainless steel orthodontic wires. Their result showed that yield strengths of grades 302 and 316 were increased by heat treatment. The largest improvement occurred between the range of temperatures 700° to 900°F

(371° to 482°C). They also noted that grade 316 exhibited higher strength properties to those of grade 302, especially was this so of yield strength which was 25 per cent greater for grade 316. It was also reported that there were sizeable variations in the mechanical properties from batch to batch of the same grade wire from the various suppliers.

Note: "Elgiloy" - Various authors have referred to "Elgiloy" as cobalt chrome alloy, cobalt chromium nickel alloy, or cobalt nickel alloy. All are acceptable, but the Elgin Booklet[56] refers to "Elgiloy" as a cobalt nickel alloy.

Precipitation-hardening Stainless Steel may be abbreviated as PH Stainless Steel.

CHAPTER 4

4. STAINLESS STEEL AND COBALT NICKEL ALLOY

4.1. STAINLESS STEEL

4.1.1. DEVELOPMENT

Three groups of people working apparently independently, appear to have shared in the discovery of rust-resisting steel; they were: (1) Brearley of Sheffield, England, (2) Strauss and Maurer of Essen, Germany, and (3) Haynes of Indianapolis, U.S.A.

Brearley first discovered a rust-resisting chrome iron in 1913 and was responsible for its further development (Alexander and Street[1], Moneypenny[39]). At about the same time or slightly earlier at the Krupps works in Essen, Drs. Strauss and Maurer had produced and applied for the patents in October 1912 for two chromium-nickel iron alloys, and the discovery of austenitic stainless steel must be credited to these two men (Gaston)[28]. Elwood Haynes of Indianapolis had also done some experimental work with chromium iron and cobalt iron alloys around 1911 and 1912. But due to a possible ignorance of the capabilities of chrome iron alloys, steel manufacturers in the United States gave little support and although Haynes' second application for patent was filed in 1915 it was not granted till 1919 (Gaston)[28].

From this record it can be seen that the Europeans were well ahead of the United States in the development of austenitic stainless

steel. Thus we find that in Europe, Lucien de Coster (1932)[20] reported he had used stainless steel for orthodontic appliances in Belgium since 1924. While American orthodontists were using platinised gold or experimenting with other materials, such as tungsten or molybdenum, Pollock (1916)[43] made reference to the work of Price and Fahrenwald in 1915 with tungsten and molybdenum and the possibility of their use in the fabricating of orthodontic appliances. He (Pollock) concluded his article "No doubt the experience of others will develop some very desirable and welcome ideas in the use of tungsten and molybdenum, which, as yet, are obscure but offer great possibilities of development in future orthodontic technique".

Paffenbarger et al (1943)[42] nominate the head of the Krupp Dental Clinic as the first to use stainless steel for oral appliances. Possibly Paul Simon (1933)[50] of Berlin was one of the first to use stainless steel in orthodontic appliances. Stainless steel was, however, not introduced into the orthodontic field in the United States till 1929 or 1930 (Gaston)[28]. Walsh (1938)[60] stated he did not obtain a satisfactory stainless steel till 1933.

4.1.2. GRADES AND COMPOSITION OF STAINLESS STEEL

There are many grades of stainless steel. They are divided into two main groups by the American Iron and Steel Institute. Those

which contain chromium in combination with nickel are prefaced by the number 3 and those which are nickel free are prefaced by the number 4. The chromium nickel alloys are the ones that are concerned with orthodontic use, namely, grades 302, 304, 316. The nickel free alloy is mainly for domestic and industrial use, for example, in the making of stainless steel cutlery.

More recently a new range of precipitation-hardening (PH) stainless steels have been developed. The most commonly used of these are 17-7 and 15-5 precipitation-hardening (PH) stainless steel.

Until the development of these newer type stainless steels, 302 18-8 stainless steel was the most commonly used in the manufacture of orthodontic wire.

The American Iron and Steel Institute list the composition of grade 302 as carbon 0.15 per cent maximum; manganese 2 per cent maximum; silicon 1 per cent maximum; chromium 17-19 per cent; nickel 8-10 per cent; sulphur 0.03 per cent maximum; phosphorus 0.04 per cent maximum; the remainder is made up of iron. Grade 304 is very similar to grade 302 in both properties and composition, it has a lower carbon content at 0.08 per cent with the range for chromium 18-20 per cent and that of nickel 8-12 per cent. Both alloys are austenitic, have a very high corrosive resistance and are non-magnetic (Kohl 1964[35]).

Type 316 differs from grades 302 and 304 in containing 2 per cent more nickel in addition to 2 per cent molybdenum. The addition of molybdenum endows grade 316 with increased corrosion resistance (Howe et al).[30]

The wire used by Wilcock of Australia is of British origin. It is covered by the composition of En 58A stainless steel as specified in British Standard 2056 (En 58A B.S. 2056); carbon 0.16 per cent maximum; silicon 0.20 per cent minimum; manganese 2.00 per cent maximum; nickel 7-10.0 per cent; chromium 17-20 per cent; nickel plus chromium 25.0 per cent minimum; sulphur 0.045 per cent maximum; phosphorous 0.045 per cent. Reference will be made later to this specification, especially to the variations possible within the nickel plus chromium 25.0 per cent minimum specification.

The Armco Product Data Bulletin S - 29a[7] lists the composition of 17-7 precipitation-hardening (PH) stainless steel as, in addition to its iron content, carbon 0.09 per cent maximum; manganese 1.0 per cent maximum; silicon 1.0 per cent maximum; aluminium 0.75 to 1.50 per cent; sulphur 0.04 per cent maximum; phosphorous 0.04 per cent maximum; chromium 16-18 per cent; nickel 6.5 to 7.5 per cent. This type of stainless steel is not as corrosive resistant as grades 302, 304, 316.

The composition of 15-5 precipitation-hardening (PH) stainless steel is listed in Armco Product Data Bulletin S-21a[6] as in addition to

its iron content, carbon 0.07 per cent maximum; manganese 1.00 per cent maximum; phosphorous 0.04 per cent maximum; sulphur 0.03 per cent maximum; chromium 14.00 to 15.50 per cent; nickel 3.50 to 5.50 per cent; copper 2.50 to 4.50 per cent; columbium plus tantalum 0.15 to 0.45 per cent.

4.1.3. HOW STAINLESS STEEL WIRE IS PRODUCED (KOHL) [35]

"Orthodontic wires are made from high density castings. When the molten casting solidifies, minute impurities which exist act as centers of crystallization. At these centers space lattices begin to attach themselves to each other. These form outward growths or dendrites which continue to grow until they meet other forming nuclei. The solid mass formed from each center of crystallization is called a crystal grain. The number of grains formed depends upon the number of original nuclei of crystallization which formed. The faster the casting is cooled, the greater will be the number of nuclei formed and, therefore, the smaller will be the grain size.

The shape of the grain may be changed by applying a force to the material. Because the grain is made of atoms arranged in the form of cubes and held in place by mutual attractions and repulsions, there are planes in this arrangement along which there is less resistance to movement than along other planes. When stress is first applied, the space lattice is slightly distorted out of shape but returns to its original position upon release of the stress. This deformation is called elastic strain. The maximum stress to

which the material may be subjected without any permanent deformation remaining upon release of the stress is called the elastic limit. If the stress is greater than the lattice can bear elastically, permanent deformation takes place and one series of atoms moves along another series of atoms. The plane along which this movement takes place is called a slip-plane. The size of the grain and the number of slip-planes present in the individual grain determine the amount of plastic deformation which can take place. The slip-planes usually do not extend entirely to the grain boundaries indicating that the grain boundaries are stronger than the material at the interior of the grain. This is probably due to a greater distortion in the shape of the space lattice at the grain boundary. This distortion causes internal friction making slip more difficult. For this reason fine-grained alloys are preferred, the more grain boundaries present, the stronger the material; also, the smaller the grain size, the greater the tensile strength and elasticity.

Grain size can be reduced by alternate plastic deformation and recrystallization. In the fabrication of wires the cast metal or ingot is rolled or drawn down to size in stages. Between each stage the wire is heated to the recrystallization temperature of the metal, thus producing smaller equiaxed grains. The drawing process elongates the grains into long fibrous structures, the long axes of the fibres running in the direction of drawing.

This mechanical adaptation or deformation of the metal is known as cold-working and the finished product is described as a wrought structure." This wire is referred to as cold or hard drawn stainless steel wire as opposed to heat-treated stainless steel wire, that is, wire that has undergone low temperature stress-relieving heat treatment after the final drawing.

4.1.4. THE HEAT TREATMENT OF STAINLESS STEEL ORTHODONTIC WIRES

The effect of low temperature heat treatment on the mechanical properties, Wilkinson in 1960 [63] stated: "The tensile strength and proportional limit of cold-worked stainless steel can be increased by low temperature heat treatment." Presumably, by releasing some of the residual strain induced by plastic deformation, he continued, "this low temperature tempering process has been applied to stainless steel orthodontic wires both before and after forming to the teeth".

Other workers have examined the effect of heat treatment on orthodontic wire. Funk (1951) [27] carried out heat treatment of stainless steel wire from 500°F to 1300°F. He concluded that heat treatment of the wire at 850°F for three minutes gave the best increase in mechanical properties.

Backofen and Gales (1951) [10] in experiments with .020 inch round and .020 x .025 inch rectangular stainless steel wires, showed a marked increase in the elastic properties of the wires when heat treated for ten minutes at 750°F or 820°F.

Kemler (1956)[34] studied the effect of temperatures up to 700°F on .020 x .025 inch orthodontic stainless steel wire. He found a significant increase in the proportional limit, modulus of elasticity and modulus of resiliency resulted from this low temperature heat treatment.

Mutchler (1961)[40] compared the effect of heat treatment on 18-8 stainless steel and cobalt chromium alloy .018 inch round wires. He found that controlled heat improved the proportional limit, modulus of elasticity and modulus of resiliency of all wires tested. The optimum temperature for stainless steel was 3 to 15 minutes at 700° to 1000°F.

Delgado and Anderson (1963)[21] considered the effect of low temperature heat treatment on various diameter round stainless steel wires. They found that the effect on the tensile strength and capacity for bending is not great enough to be of use in clinical practice.

Ingerslev (1966)[31] worked on the effect of heat treatment on stainless steel formed archwires. He found that heat treatment produced change in the elastic limit for expansion and compression of the arches. This was due to the relieving of internal stresses introduced during the cold working of the wire. He also noted that 18-8 stainless steel should not be heated above 400°C (752°F) as this reduces the resistance to corrosion.

Howe et al (1968)[30] tested grades 302 and 316 stainless steel wires. As a result of these tests they concluded that heat treatment at 750°F to 850°F increased the mechanical properties of the wires tested. Especially was this so of the yield strength.

Thus it can be seen from the many studies already carried out that low temperature heat treatment of stainless steel orthodontic wire, especially after the final cold drawing process has many benefits, in the way of increased mechanical properties, to offer to the orthodontist. In a very special way does this apply to those who work with the Australian (Begg) Light Wire Technique, as with the raising of the proportional limit following this heat treatment, a more resilient wire is obtained.

It can also be noted that the approximate temperature for low temperature heat treatment lies between 700°F and 850°F (371°C to 484°C), this is below the recrystallization temperature of stainless steel. If the wire is heated above this level we get recrystallization and eventually grain growth in the stainless steel with associated softening of the material. This has been reported on by Wilkinson in 1960[63], he stated: "While it is known that the wires can be tempered in the heat range 260°C to 460°C (500°F to 850°F) higher temperatures allow recrystallization of the metal. When this occurs the long fibrous grains re-form

TENSILE STRENGTH OF ORTHODONTIC WIRES

Type of Wire	Tensile Strength		
	lbf/in2 (1000's)	tonf/in2	kgf/mm2
A	250-325	112-145	176-228
B	326-370	146-165	229-260
C	371-390	166-174	261-274
D	391 and over	175 and over	275 and over

Table 1 - Classification Specifications Australian Standard T32.

STRENGTH AND CLASSIFICATION (T32) OF ORTHODONTIC WIRES.

BRAND	NUMBER TESTED	RANGE OF DIAMETERS IN INCHES.	TENSILE STRENGTH		NUMBER FALLING IN T32 CLASSIFICATIONS
			TON f / INCH 2	1000 lb f / INCH 2	
ASH	8	0·016 — 0·032	101 — 145	226 — 325	8 A
ASSAB	4	0·015 — 0·016	141 — 155	316 — 352	2 A 2 B
ARMCO	5	0·015 — 0·30	101 — 126	226 — 282	1 LOW 4 A
ELCILOY RED	4	0·016	141 — 145	316 — 325	4 A
BRUNTONS	5	0·020 — 0·032	101 — 124	226 — 278	2 LOW 3 A
ROCKY MOUNTAINS TRUCHROME	12	0·008 — 0·032	126 — 154	282 — 345	6 A 6 B
TEMCO	9	0·010 — 0·031	101 — 156	226 — 349	8 A 1 B
S S W C	32	0·008 — 0·032	101 — 200	226 — 448	3 LOW 2 D 3 C 7 A 17 B
UNITEK	20	0·012 — 0·030	100 — 145	224 — 325	5 LOW 15 A
UNITEK Hi T	2	0·016	172 — 177	385 — 396	2 C
WILPA	3	0·016 — 0·024	106 — 131	237 — 293	1 LOW 2 A
WILCOCK	50	0·008 — 0·032	REGULAR 145–155 REGULAR+ 156–165 SPECIAL 166–175 SPECIAL +176–185	325 — 352 353 — 370 371 — 391 392 — 415	B B C D

Table 2 - Strength and Classification of Resilient Wires of 0.016 inch Diameter.

(Ware, Australian Orthodontic Bulletin Jan. 1967)

into roughly equiaxed grains, and the wire loses the properties developed by the plastic deformation."

4.2. EXPERIMENTAL STAINLESS STEEL WIRES

All wires tested were nominally .016 inch diameter round wire.

The stainless steel wires tested were:

(1) Wilcock Wire, better known in overseas orthodontic circles as "Australian Wire", manufactured by A.J. Wilcock, Whittlesea, Victoria, Australia.
All Wilcock Wires as used had already been stress-relieved by low temperature heat treatment prior to leaving Wilcock's factory.

(2) Dentaurum Remanit "Super Spring Hard", from Firma Dentaurum, Pforzhein, West Germany. Marketed in U.S.A. as "Boomerang Wire".
The "Super Spring Hard" wire in the as-received condition had also undergone heat treatment.

(3) "Unisil" from Unitek Corporation, Monrovia, California, U.S.A. "Unisil" was received in the cold-worked condition.

4.2.1. WILCOCK WIRE

The complete range of Wilcock "Special Plus", "Special", "Regular Plus" and "Regular", were chosen from the normal supply provided for use in the University Orthodontic Clinic, Department of

Preventive Dentistry, Sydney. Four coils of each type wire were chosen, each individual type being from a matching batch. The particular batch numbers were:

Special Plus, D.RCC.	Special, W.RCW.
Regular Plus, I.RIK.	Regular, I.RWI.

The Commonwealth Bureau of Dental Standards (Jan.1967)[61] graded and certified these wires according to Australian Standard T32 (see Table 2). The gradings were:

Special Plus	-	Type D
Special	-	Type C
Regular Plus	-	Type B
Regular	-	Type B

As Wilcock has been closely associated with Begg in the development of his technique, in so far that he has provided the high tensile wire which Begg uses and recommends, it seems appropriate, therefore, to describe this wire drawing process with which Wilcock has achieved such success.

4.2.2. THE WIRE DRAWING PROCESS AS FOLLOWED BY A.J. WILCOCK[62]

Selection of Wire

All the wire used by Wilcock in the manufacture of .016 inch diameter orthodontic wires is supplied by Samuel Fox of Sheffield, England. The composition of this wire is that laid down for En 58A stainless steel as covered by British Standard 2056[16] (En 58A B.S. 2056). See Page 34 for composition.

There are three important facts which must be known about the wire chosen for drawing:

(1) Composition

(2) Tensile Strength

(3) Diameter of Wire

(1) Composition: Wilcock insists on and is supplied with a complete analysis of the constituents of each batch of wire he receives from Fox of Sheffield. The importance of this analysis is obvious if one studies the composition for a En 58A stainless steel. It is possible within the range of composition allowing for a minimum 25 per cent chromium nickel content to have a variation from 17.5 per cent chromium 7.5 per cent nickel through to a 19 per cent chromium 9 per cent nickel. Wilcock told me, however, it was rare to find a 19-9 stainless steel. Thus the range is restricted between 17-5/7-5 and 19-8.

(2) Tensile Strength: With the variation in composition there is also coupled varying ranges of tensile strengths depending on how much cold working the wire has already received.

(3) Diameter of Wire: Wilcock commences the drawing process for a .016 inch "Special Plus" wire by starting with a .022 inch initially and reducing it by .002 inch in subsequent drawings down to the desired size. With an .016 inch "Regular" wire he may only use a .018 inch wire initially and draw it the once. From this it can be seen that there are an incalculable number of variations with which Wilcock has to contend.

by careful selection, using his experience and records, Wilcock is able to select from the batches of wires he receives, the batch with the ideal combination for use in his various range of wires from "Special Plus" through to "Regular".

Drawing Process

When Wilcock first receives the wire it is in various forms of packaging. It is immediately wound onto spools.

Initial Heat Treatment and Oxidation

These spools are then placed in an oven where the wire is oxidised during heat treatment. Wilcock has told me he even forces oxygen through the oven on some occasions to ensure adequate oxidation. Not only does this process clean the wire it also leaves it with a roughened surface. The need for this will be explained later.

The spool of oxidised wire is now placed on a spindle and the wire threaded along the wire drawing bench and onto a variable speed shaft and finally onto another spool. The wire is now set up for drawing.

The Stages in this process are:

Lubricant Bath (Composition of lubricant not disclosed)

Immediately the wire leaves the coil it passes through a small trough about six inches long filled with lubricant. The purpose of the original oxidation was to ensure that the lubricant would adhere to the wire. This is essential as the purpose of the

lubricant coating is to protect the dies as the wire passes through during the drawing process. Especially is this so when drawing the high tensile wire.

Drying

On leaving the lubricant bath the wire passes over a series of small gas jets for a distance of approximately two feet. This initially sets the lubricant on the wire. From here the wire travels along about 12 to 15 feet while it dries in the air.

Stearate Powder

After the drying process, the wire goes through a small mound of stearate powder placed on the bench about one foot before it enters the dies. This also acts as a further lubricant.

The Dies

The wire is guided into the double diamond dies which are a pressure-operated type.

Tapered Wheel then Spool

When the wires pass through the die they are fed on to a large tapered wheel about 12 inches in diameter. After making one circuit of this wheel the outer strand of wire is taken off onto another spool.

Essential Points of this Process are:

The speed of drawing "Special Plus" and "Special" are drawn at a speed of three feet per minute. "Regular Plus" and "Regular" are drawn at eight feet per minute.

Heat Treatment (Temperature of heat treatment not disclosed)

As previously stated the wires are drawn down from .022 inch to .016 inch by a series of .002 inch reductions per drawing. After each drawing the wire is heat treated, as noted the actual temperature of treatment is not available. All that Wilcock will let me say is that the process is "more than a stress-relieving process". The heat treatment following the final draw would no doubt be only a stress-relieving process.

Packaging

The wire is packaged in Australia in 25 foot coils in cellophane bags which readily tear. In the United States, however, "Australian Wire" is sold in neat plastic containers clearly marked by T.P. products.

4.2.3. DENTAURUM REMANIT

The wire was purchased from the agents Rudolf Gunz and Company of Sydney. Four coils of "Super Spring Hard" wire were obtained. No individual batch number was listed on the containers.

Original Manufacture (Personal Communication)[22]

The wire which the Firma Dentaurum distribute is produced for them by Stahlwerke (Steelworks) Ergste GmbH and Company of West Germany. The original supplies of wire for drawing purposes come from either D.E.A. or Krupps. (It is more likely to be D.E.A. Steelworks.)

Composition

The Stahlwerke Ergste give the composition of the wire Argeste 80 S.G. which is used for drawing, as corresponding to German Standard No. 4568. This is a 17-7 precipitation-hardening stainless steel. The figures given by the company cover the essentials only: carbon 0.07 per cent; chromium 16.5 per cent; nickel plus aluminium 6.5 per cent.

They also state that the composition is very similar to that of the American Armco norm 17-7 precipitation-hardening stainless steel[7]. The company states that the U.T.S. has little bearing on the performance of the wire; they are more concerned with the elastic limit, or proportional limit. They claim still further that the elastic limit of their heat-treated wire is very close to the U.T.S. of the wire. Thus, although the U.T.S. may seem lower than those of Wilcock wire, the elastic limit or proportional limit is very close to the figure for Wilcock wire.

The work of Craig et al (1965)[19] on 17-7 precipitation-hardening stainless steel would support these statements. They found that the yield strength (proof stress) was approximately 90 per cent of the value of the U.T.S. after heat treating and that even in the cold-worked martensitic condition the yield strength (proof stress) was superior to that of 18-8 stainless steel.

With regard to the composition of Wilcock "Special Plus", Stahlwerke Ergste say their analysis of the wire (i.e. Wilcock's wire)

shows a chromium content of 17.08 per cent and a nickel content of 8.31 per cent. These figures seem reasonably acceptable as the British Standard 2056 sets a minimum chromium/nickel content of 25 per cent.

Packaging

The wire is packaged in Germany and comes in approximately 25 feet coils in a metal backed clearly marked container.

4.2.4. UNISIL

Four coils of "Unisil" wire were obtained direct from Unitek Corporation. The containers were marked only with a catalogue number 354-160, no actual batch numbers were given.

Original Manufacture (Personal Communications)[58]

The wire which Unitek Corporation market as "Unisil" wire is produced for them by a steel company, referred to by them in a letter to the author as the N.S. Company. This is most likely the National Standards Corporation of Niles, Michigan.

Composition

Unitek forwarded a copy of the original procurement specifications. From these sheets it could be noted that the composition of the wire would be that of an NS-355 High Tensile Stainless Steel Spring Wire. Typical chemical analysis listed by Unitek is:

carbon .142 per cent; manganese 1.00 per cent; phosphorus .027 per cent; sulphur .013 per cent; silicon .32 per cent; chromium 15.65 per cent; nickel 4.38 per cent; molybdenum 2.68 per cent;

copper .12 per cent; nitrogen .124 per cent. The remainder of content is iron. These figures indicate that the wire is a 15-5 precipitation-hardening stainless steel.

Tensile Properties

The specifications also stated that the wire must have a tensile strength of a minimum 380,000 maximum 400,000 pounds per square inch.

Packaging

The wire is packaged in the U.S.A. in 25 feet coils and comes in a clearly marked easily used plastic container.

4.3. ELGILOY (COBALT NICKEL ALLOY)

4.3.1. DEVELOPMENT (Elgin Booklet) [56]

Why and how "Elgiloy" was developed might be best explained by quoting from the introduction to the Elgin Company's booklet on this wire.

Before the Elgin National Watch Company developed "Elgiloy", it faced a problem that has troubled watch manufacturers since the art of watch making began. At that time, a high percentage of all watch failures were caused by mainspring breakage. The problem was to find a material that would eliminate this cause of failure. The mainspring material desired by watch makers prior to World War II was generally thought to be impossible to attain because of the complex properties demanded. It must be a non-magnetic material which would not rust or break and at the same

time offer high resistance to set and fatigue. None of the materials available satisfied Elgin's high mainspring standards.

Since such a material simply just did not exist, Elgin's Research Department initiated a project to work closely with Battelle Memorial Institute to find a suitable material. After years of research and testing, a material was found that not only filled Elgin's specifications but far exceeded its highest hopes. Since it was to be "Elgin's Alloy", it was trademarked "Elgiloy".

As the amazing properties of this material became known to industry, Elgin began to receive requests for parts to be fabricated from "Elgiloy". The parts were to be used in the widest variety of industrial applications. As the number of these industrial applications increased, further research was undertaken to meet industrial needs which, in many cases, were far afield from the original mainspring application.

The Rocky Mountain Metals Products Company was selected to develop "Elgiloy" for orthodontics.

4.3.2. GENERAL PROPERTIES (Elgin Booklet) [56]

The properties quoted by the Elgin Company are:

(1) Extremely high resistance to corrosion.

(2) High resistance to set.

(3) Greater spring efficiency.

(4) Excellent resistance to fatigue.

(5) Temperature resistant from - 85° to 1000°F.

(6) Non-magnetic from 200°F to 1000°F.

In some cases "Elgiloy" is being used for one particular property. However, in the majority of cases "Elgiloy" is used to take advantage of a combination of its properties.

4.3.3. COMPOSITION OF ELGILOY (Elgin Booklet) [56]

"Elgiloy" is a cobalt base alloy which derives its maximum properties from a combination of cold work and heat treatment. It is not a true precipitation-hardening alloy since the amount of response to heat treatment is a function of the amount of cold work. It is important to note, therefore, that once "Elgiloy" is annealed the cold work is lost and "Elgiloy" will not regain its maximum properties with further heat treatment.

"Elgiloy" combines the excellent strength characteristics and corrosion resistance of cobalt with the added corrosion resistance of chromium plus the strength and ductility of nickel. Molybdenum is added to increase the mechanical properties at elevated temperatures. The remaining elements provide the additional properties of hardenability and set resistance. The nominal composition of "Elgiloy" is as follows:

NOMINAL COMPOSITION

(Patented U.S. Pat. No. 2524661)

Cobalt	40%	Manganese	2%
Chromium	20%	Carbon	0.15%
Nickel	15%	Beryllium	0.04%
Molybdenum	7%	Iron	Balance

4.3.4. AVAILABILITY OF ELGILOY ORTHODONTIC WIRES (Rocky Mountain Booklet) [46]

Rocky Mountain Metal Products Co. has developed a series of different types of "Elgiloy" wires, in order to provide a wide range of wires with varying properties. Each type is fabricated for specific applications, and each is identified by a colour marking on the end. Four colours identify the different types of "Elgiloy" wire. These colours appear on the tips of each length of wire (Rocky Mountain Booklet).

RED, "Spring temper wire" is ready-to-use, as working arch wire. It can be shaped with the fingers, but it will not take sharp bends by pliers. If greater spring qualities are desired, any of several heat-treating procedures can be applied. After heat-treating red wire will fracture, if bent or adjusted sharply. Red tipped "Elgiloy" is excellent for twin arch and similar small wire techniques.

GREEN, "Semi-spring temper wire" is excellent for certain round wire arches, as it can be shaped and bent slightly with fingers and pliers without fracturing. It is recommended that the efficiency of the wire be increased by heat-treating after initial adjustment - or shortly after the case has been started. (Green wire will fracture after heat-treating, if bent severely.) Green tipped "Elgiloy" is recommended for starting arches in edgewise techniques.

YELLOW TIPPED WIRE is ductile. It can be bent considerably with fingers and pliers without fracturing. Yellow wire is to be heat-treated after initial bending. (Yellow tipped "Elgiloy" will allow only minute adjustments after heat-treating.) It is excellent for labial arches, soldered linguals, retainers, flat and ribbon arch techniques, Crozats, and for small .015, .016 and .018 inch auxiliary springs.

BLUE TIPPED WIRE is soft and more ductile than yellow wire. It is easily shaped and bent with either the fingers or pliers. Heat-treating brings the wire up to an ideal spring temper, which permits it to be adjusted slightly more than yellow wire after heat-treating. Blue tipped "Elgiloy" is especially effective for edgewise arches, plier-formed Ellis Lingual Arches, and for auxiliary springs larger than .018 inch.

(Important Note: Mechanical properties differ considerably between different color types. Rocky Mountain has also developed very slight differences in properties in the wires within each color type. This is to provide uniformity of "feel" and performance within each group. As a rule, the smaller the diameter or cross section, the greater the spring performance and general mechanical properties.)

4.3.5. BENDING AND MANIPULATION OF ELGILOY ORTHODONTIC WIRES

"Elgiloy" work-hardens even faster than Chrome Steels, so proper bending methods must be used. It is essential to bend the wire slowly.

Heat Treatment (Rocky Mountain Booklet)[46]

The mechanical properties of "Elgiloy" can be greatly enhanced by heat-treating. It should be noted that each different colour type will produce different end results after heat-treating. The "stiffer" the wire is in its raw state, the "stiffer" it will be after heat-treating. For instance, the general physical properties of a "Red Elgiloy" wire after heat-treating exceed those of a "Blue Elgiloy" wire after heat-treating. With "R.M. Elgiloy" you have a truly complete range of properties with which to work.

Although "Elgiloy" is best heat-treated by relatively long commercial furnace procedures, you can get effective results with "R.M. Elgiloy" for orthodontics using any of several simple heating methods. You can use a dental furnace, a soft brush flame, or you can apply electric resistance heat-treating attachments for certain Rocky Mountain welding and electro-polishing machines. Those most suited for use on .016 inch diameter wires are:

Dental Furnace.- "Elgiloy" is heat-treated commercially by specially controlled atmospheric furnaces. As a rule, one to five hours heat-treating at 900°F produces best results. This, of course, is not practical for most orthodontists.

However, very effective results can be produced for the small orthodontic materials using a standard dental furnace at 900°F for lesser periods of time. Seven minutes seem to be the minimum.

4.3.6. RESISTANCE HEAT TREATING

The heat-treating attachments on late model Rocky Mountain machines provide exceptionally convenient means of heat-treating "R.M. Elgiloy" materials.

4.4. EXPERIMENTAL WIRE

4.4.1. RED ELGILOY

The wire chosen for this project was "Red Elgiloy" nominally .016 inch diameter this batch was also labelled 0.41 mm. and on measuring the diameter was .0156 inch.

There is little information currently available concerning the properties of this particular wire. All details given previously have come from Booklets printed in 1957-59 era.

The wire used was heat treated for seven minutes at 900°F (482°C) in a dental furnace.

CHAPTER 5

5. THE ELASTICITY AND STRENGTH OF MATERIALS

To allow explanation of the experimental research undertaken, it is appropriate, at this stage, to present the theoretical principles and terminology involved in the testing of the elastic and plastic properties of the wires concerned.

5.1. STRESS, STRAIN AND ELASTICITY

Section 5.1.1. through to, and inclusive of, Section 5.1.4. are taken from the textbook "Materials and Structures" by E.H. Salmon[47]. All other definitions are from Metals Handbook 8th Edition[38] unless otherwise specified.

5.1.1. ELASTIC MATERIAL

When making an analytical study of the effect on a body of distorting forces, it is customary to assume that the material of which the body is composed is perfectly elastic. That is to say, it is assumed that not only do all effects of the distorting forces immediately disappear on removal of those forces, but that the distortion produced in the material is proportional to the magnitude of the effort which gives rise to it. It is further assumed that the material has the same elastic properties in every direction. Such material is called isotropic material. No engineering material completely satisfied this ideal, but many approximate closely if the distortion produced be not too great.

The theory given below can be safely applied to these materials provided that a certain limit, called the elastic limit, be not overstepped.

5.1.2. TENSILE STRESS AND STRAIN

Suppose that a bar of length l be subjected to two longitudinal forces F F, directed along its axis, as shown at (i) Figure 5. Careful measurements will show that, as a result, the bar has lengthened by a certain amount, which will be denoted by δl. This alteration in length δl is called the elongation produced by the forces F F.

The ratio $\frac{\text{extension}}{\text{original length}} = \frac{\delta l}{l} = S$ . . . . . (1)

is termed the strain. Evidently the strain is the alteration of length per unit length of the bar, for if $l = 1$, $S = \delta l$.

Owing to the action of the external forces F F, internal molecular forces, or stresses, will be set up in the material of the bar; and at any cross-section such as K K (ii) Figure 5, if the area be a and the intensity of molecular force or stress produced be f per unit area, it is evident that for equilibrium

$$F = a f; \quad \text{or} \quad f = \frac{F}{a} \qquad \text{. . . . . (2)}$$

By the expression stress, therefore, is to be understood the intensity of internal force called into play by the external forces. This intensity is expressed as units of force per unit of area. Since, in the example under consideration, the chief

deformation produced is an extension, the bar is said to be in tension, the stress is called tensile stress, and the corresponding strain a tensile strain.

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

$$\frac{\text{stress}}{\text{strain}} = \frac{f}{S} = f. \frac{1}{\delta 1} = \text{constant} = E \quad . \ . \ . \ (3)$$

where E is the tensile modulus of elasticity, often called Young's Modulus.

It follows, therefore, that

$$\frac{f}{E} = \frac{F}{Ea} = \frac{\delta 1}{1}; \text{ or } \delta 1 = \frac{Fl}{Ea} \quad . \ . \ . \ . \ . \ . \ (4)$$

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

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

Alternatively, in such a case as Figure 5, f in eq. (2) may be regarded as the average stress over the cross section. Young's Modulus or the modulus of elasticity is a measure of stiffness or

rigidity, the higher its value, the greater the stress needed to produce a given deformation and the stiffer the material.

5.1.3. COMPRESSIVE STRESS AND STRAIN

If the direction of application of the forces F F be reversed, the bar will be in compression instead of tension (iii) Figure 5. The alteration of length will be a contraction instead of an extension, and the stress and strain produced will be a compressive stress and compressive strain respectively. The ratio of compressive stress to compressive strain will be the compressive modulus of elasticity, which may be taken as equal to E, the tensile modulus. The same relation and equations will hold for compressive stress and strain as for tensile - in fact one may be regarded as a negative form of the other.

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

5.1.4. SHEAR STRESS AND STRAIN

Suppose A B C D to be a projecting length l of a body rigidly held at A D and acted on by force F at B, as shown in Figure 6. It will be assumed that the length l is so short that the bending set up is negligible. Under the action of the force F the body will defore the rectangle A B C D becoming the parallelogram A B'C'D'. This

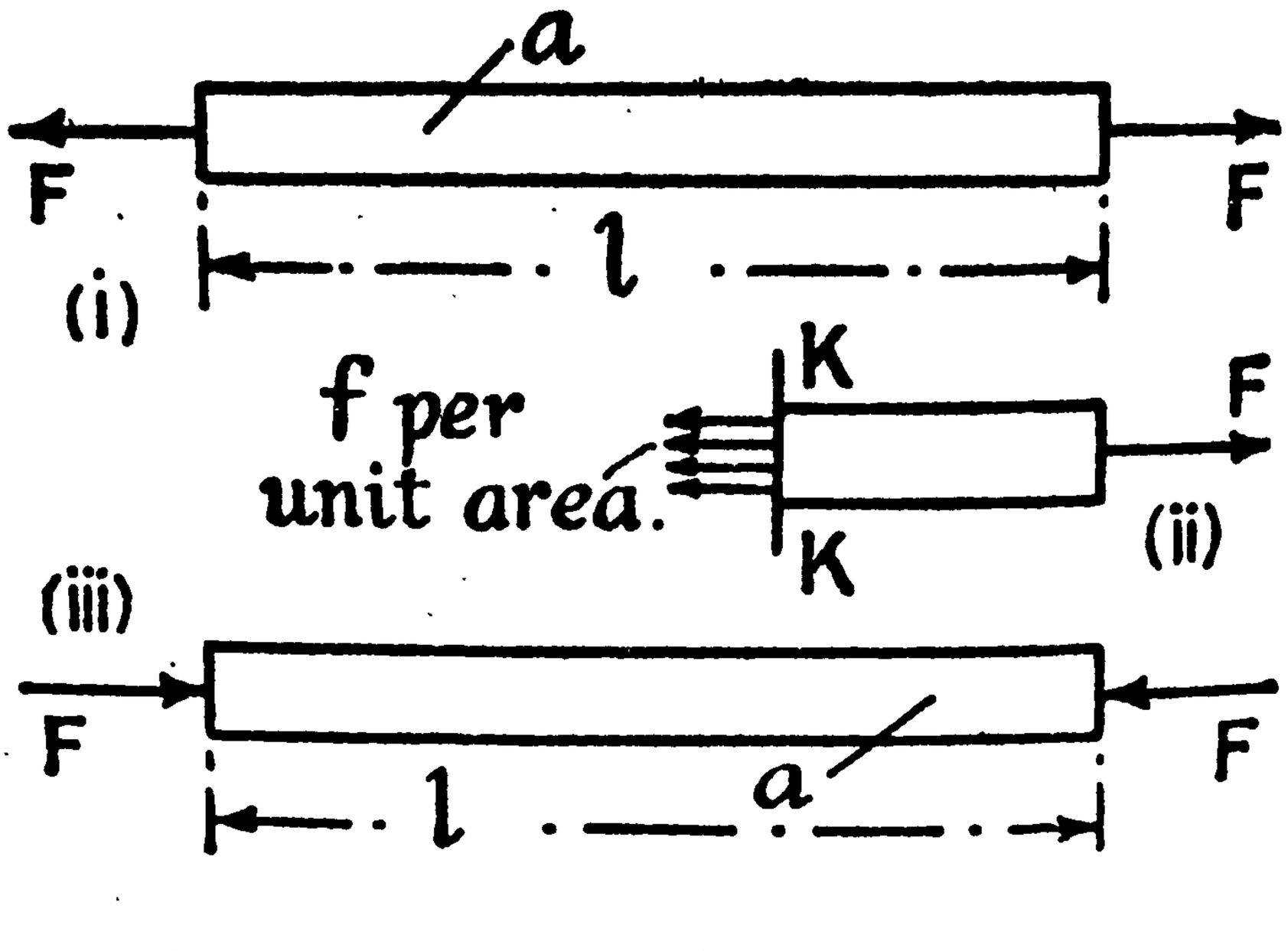


Fig. 5 - Forces on a Longitudinal Bar.

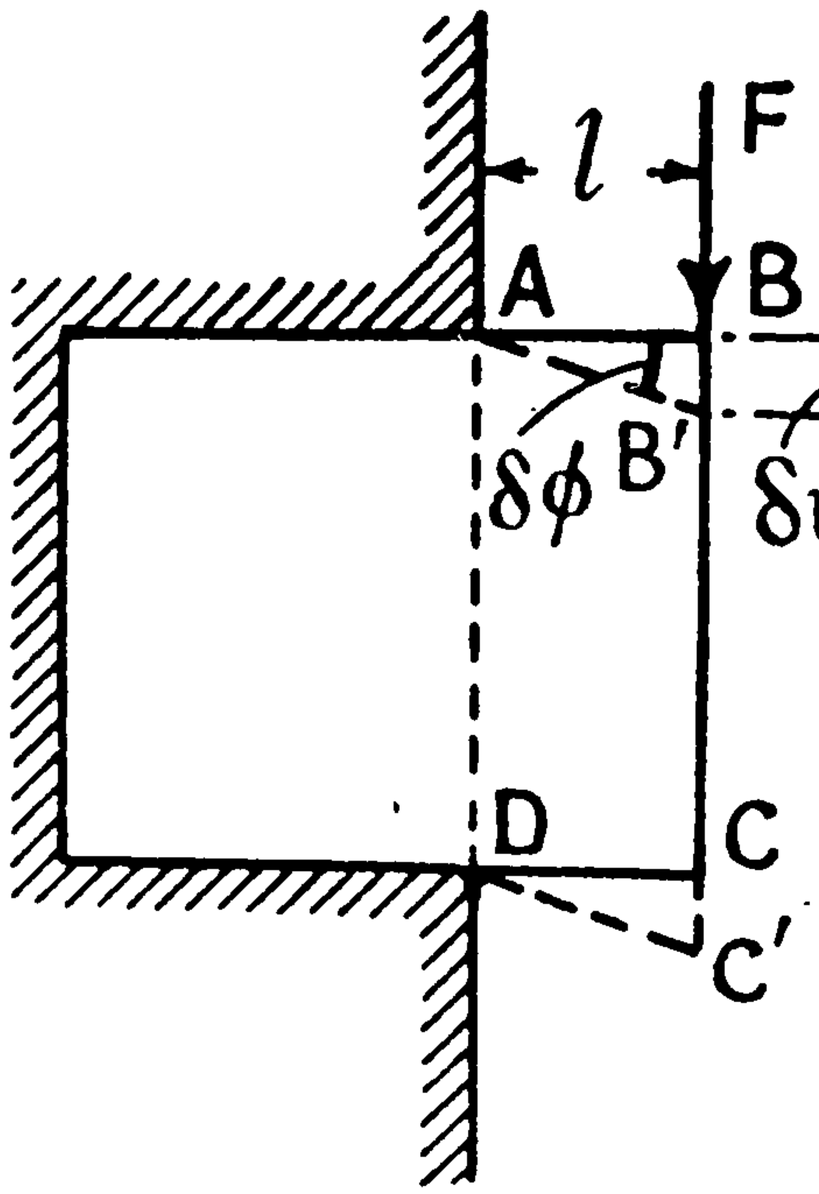


Fig. 6 - Shear Forces on a Rigid Bar.

kind of deformation is called shearing, and the angle B A B' $= \delta\phi$, which is a measure of the deformation, is called the shear strain. The angle $\delta\phi$ is expressed in radians, and, since it will be very small, $\delta\phi = \frac{B\ B'}{A\ B}$. If a be the cross section of the body, the average intensity of the shear stress is $fs = \frac{F}{a}$; and, as in the case of tensile and compressive stress and strain, it is found that, in elastic material, the ratio of shear stress to shear strain is constant. Hence,

$$\frac{\text{shear stress}}{\text{shear strain}} = \frac{fs}{\delta\phi} = \text{constant} = G \quad \ldots\ldots (5)$$

or, $\delta\phi = \frac{fs}{G}$, where G is the modulus of elasticity in shear, often called the modulus of rigidity, a quantity corresponding to the tensile modulus E, but not equal to it.

Eq. (5) may be written

$$\frac{fs}{G} = \frac{F}{Ga} = \delta\phi = \frac{\delta y}{l} \quad \ldots\ldots (6)$$

where B B' is denoted by δ y.

5.1.5. STRESS-STRAIN RELATIONSHIP

Earnshaw[23] gives as a convenient example of stress-strain relationship, a wire in tension Figure 7. Assuming the wire is made of some non-ferrous metal, if it is loaded gradually in small increments, and if measurements are made of the extension produced by each increment, then a series of readings can be obtained of load against extension, right up to the breaking load.

Knowing the original cross sectional area of the wire, loads can be converted to stresses and similarly, from the original length extensions can be converted to strains. The results obtained from loading the wire enable us to plot stress against strain for each load increment, and so draw a stress-strain curve for that material. A typical stress-strain curve for the material specified is shown in Figure 8. From a stress-strain curve like this we can define many properties which are important in consideration of metals and alloys under load.

The first part of the stress-strain curve, O A in Figure 8 is substantially a straight line. The material is obeying Hooke's Law, and its behaviour is elastic. We call O A the elastic range; stresses in this range are elastic stresses and we can say that only elastic deformation has taken place. If the load is removed at any time in the range O A, to all intent and purpose the strain returns to zero. If loads are reapplied, the new stress-strain curve follows the original one (i.e. the material is deforming elastically).

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

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

5.1.6. PROPORTIONAL LIMIT can be defined as the maximum stress at which stress is directly proportional to strain.

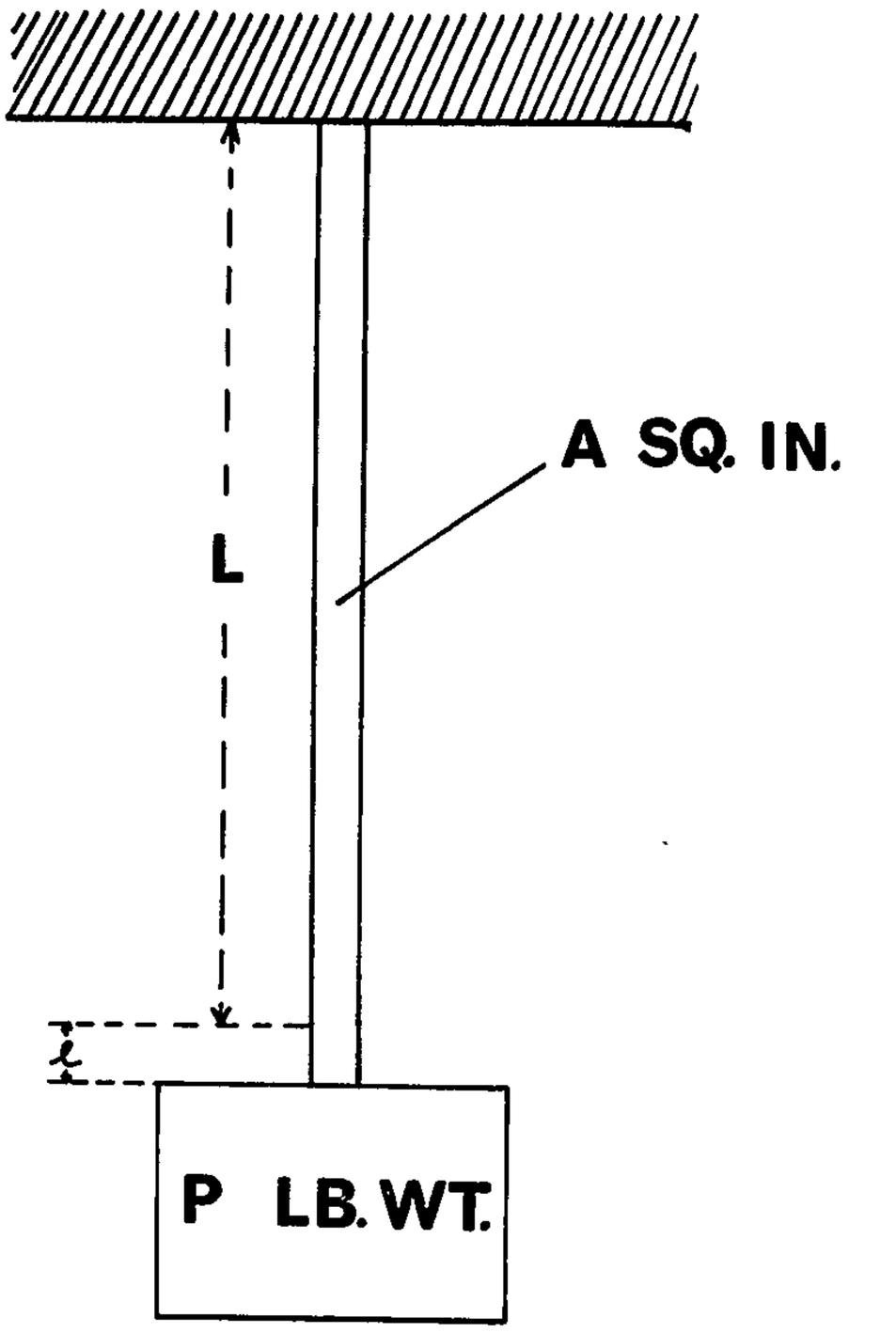


Fig. 7 - Wire in Tension.

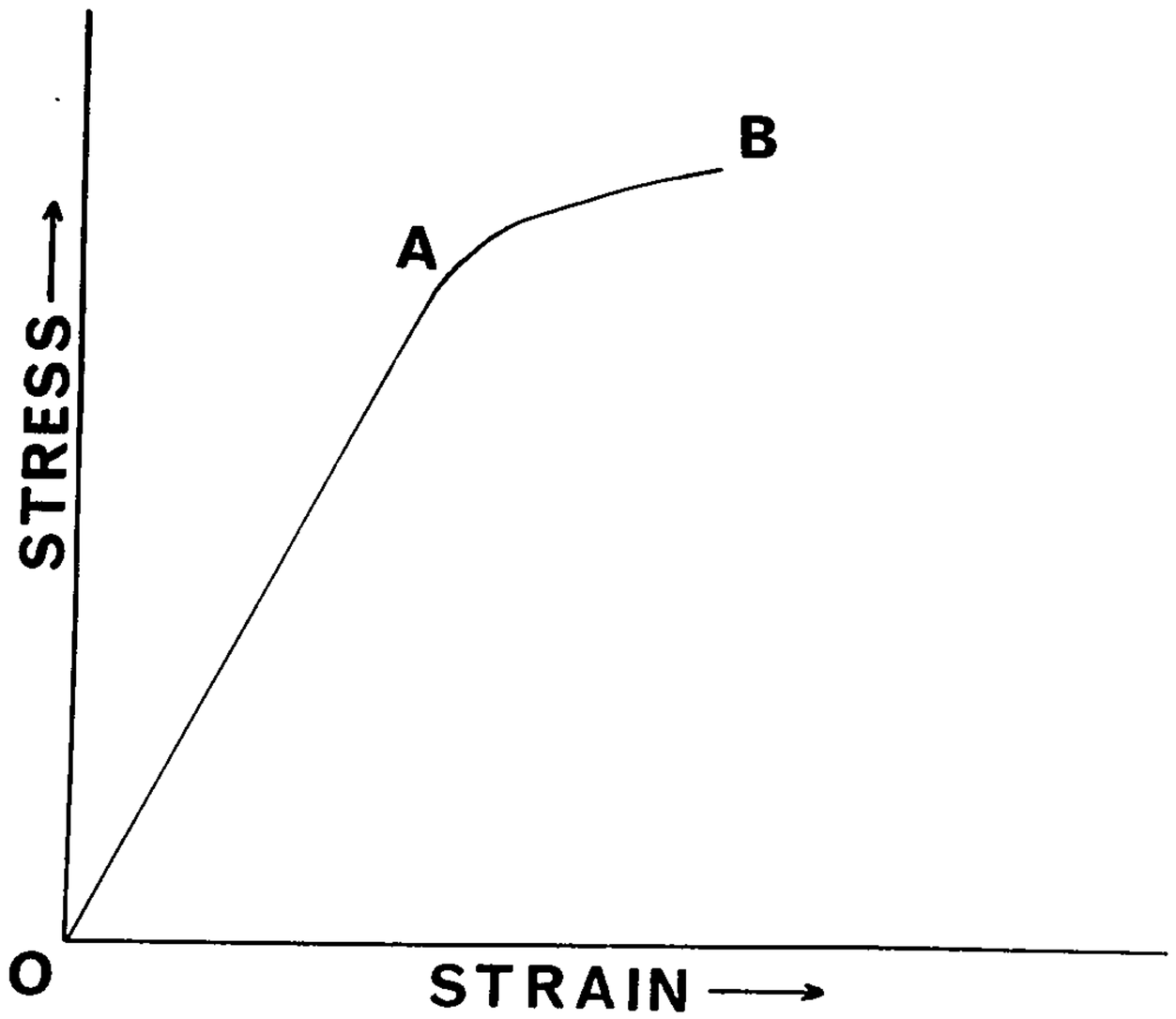


Fig. 8 - Typical Stress-Strain Curve.

Elastic Limit

The elastic limit is the maximum stress to which a material may be subjected without any permanent strain remaining upon complete release of stress. Salmon[48] states that the term "elastic limit" has been very loosely employed. It is sometimes used to denote

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

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

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

In recent years (iii) is usually called the proportional limit. In mild steel it differs very little from (i). Very refined measurement, however, has shown that materials are only perfectly elastic under very low loads, for most materials very early develop minute permanent sets. Some experiments have given very low values for the elastic limit; but the term "proportional limit" is usually used to denote the point at which marked divergence from proportionality first appears. To avoid confusion it is better to speak of the "proportional limit" and "yield point", and not to use the terms "elastic limit" and "commercial elastic limit".

The properties related to elastic behaviour are called elastic properties. These are modulus of elasticity or Young's Modulus and resiliency (Earnshaw)[23].

5.1.7. MODULUS OF ELASTICITY OR YOUNG'S MODULUS (E) is the constant expressed by the slope of the straight line O A in Figure 8. It is the relation of stress to strain in the elastic range, and is constant for a given material in a given state.

5.1.8. STRAIN ENERGY : RESILIENCE

Resilience can be defined as:

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

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

Work Done in Stretching a Bar (Salmon) [49]

Let A B (Figure 10) be a bar of length l, attached at its upper end A, and loaded at its lower end B, with a tensile force which gradually increases from zero to some value W. As the load increases the bar will lengthen; and, while the material remains elastic, the stress will be proportional to the strain, therefore the increase in length δl will be proportional to the load W. The triangle o m n will represent the relation between δl and W, that is to say, the increase in l for increasing the values of W. Now the work done on the load in stretching the bar is equal to the average force W/2, multiplied by δl the distance moved. Hence the work done is $\frac{1}{2} W . \delta l$ which is equal to the area of the triangle o m n. This energy is stored up in the bar and is called the strain energy. If the area of the bar be a, and the

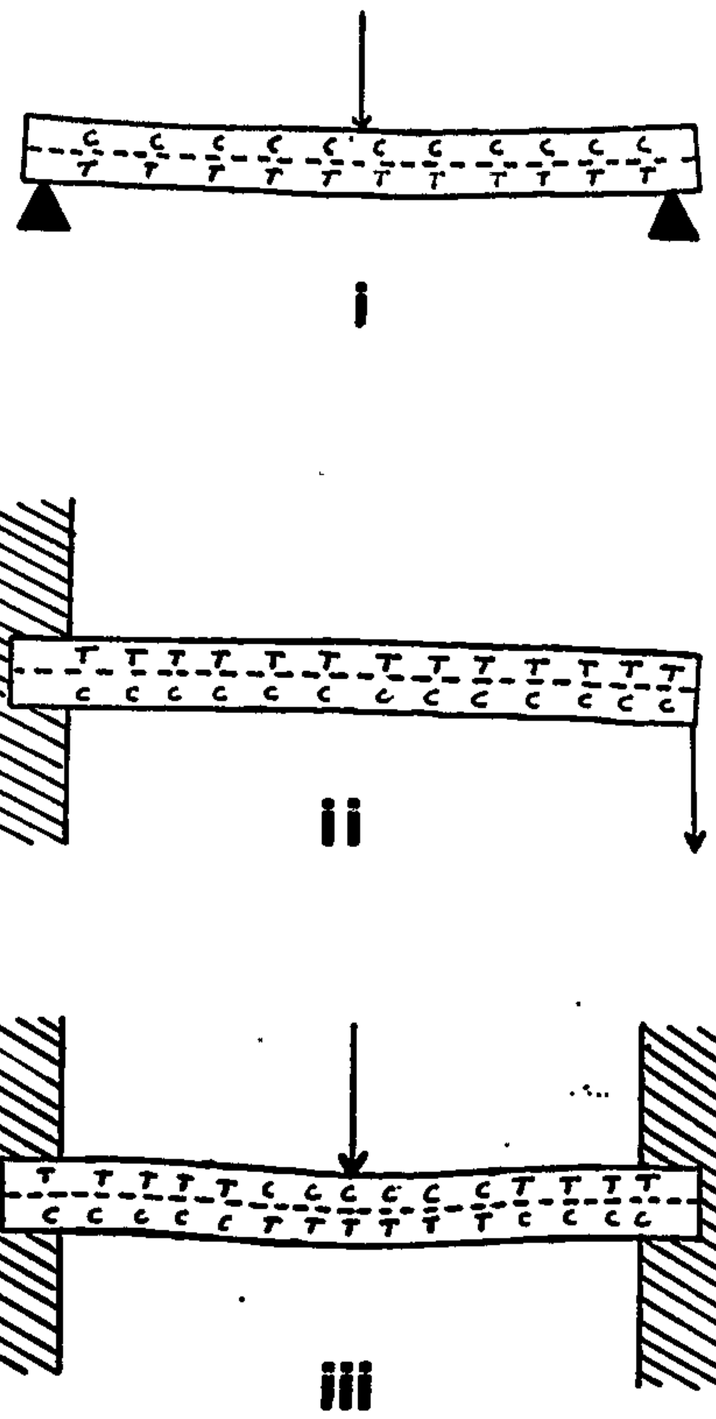


Fig. 9 - Beams-Bending

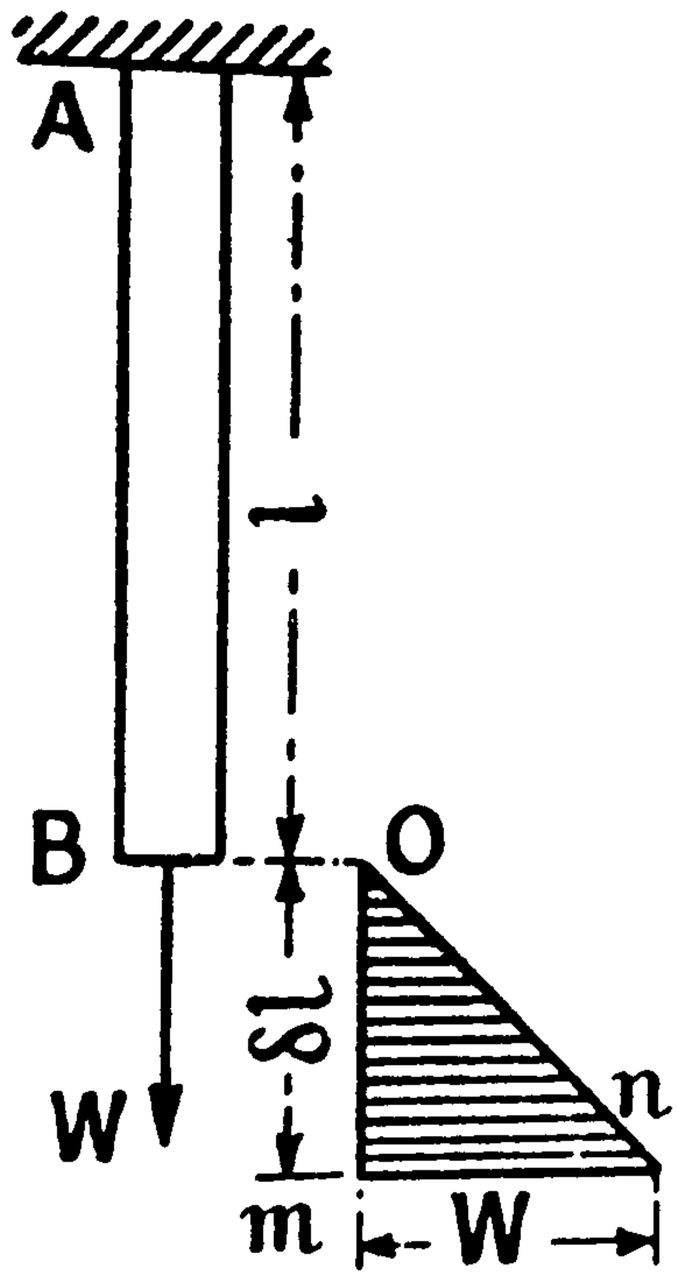


Fig. 10 - Work done in Stretching a Bar.

stress due to the load W be f, then $W = fa$. Further, the stress is equal to E times strain, and the strain is $\frac{\delta 1}{1}$. Therefore, $f = E\frac{\delta 1}{1}$, and $\delta 1 = \frac{f1}{E}$. If U be the strain energy,

$$U - \frac{1}{2} W. \delta 1 = \frac{1}{2} fa \frac{f1}{E} = \frac{f^2}{2E} \quad al = \frac{f^2}{2E} \times \text{(volume of the bar)}$$

for a.l is the volume of the bar, or as it is sometimes called the internal work. If the load W. be increased until the stress f reaches the upper limit of elasticity of the material, the strain energy then stored up in bar will be the minimum amount of work which can be done on the bar without permanently deforming it. This amount of work is called the resilience of the bar. The load producing this stress is the proof load W_p, and the stress is called the proof stress f_p. If U_p be the resilience

$$U_p = \frac{f_p^2}{2E} \text{ (Volume of the bar)}$$

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

The above case is considered by Wahl[59] to be an ideal spring, since the bar is loaded axially, the stress distribution across the section is uniform and for this reason this case represents the optimum condition from the viewpoint of maximum storage per unit volume of material.

5.2. PLASTIC DEFORMATION

Plastic deformation is occurring in the range A - B, but elastic strain is still present. If the load is removed at some stage in the plastic range, elastic recovery or "spring back" occurs, e.g. in Figure 11; if the load is removed at C the material recovers along the line C - D, parallel to the original elastic section O - A. Thus, after the load is removed there is still some strain present, measured by O - D; this represents the plastic deformation performed in the section A - C of the stress-strain curve and is called permanent set, and is defined as the plastic deformation that remains upon releasing the stress that produces the deformation. If the material is then reloaded, the unloading curve is retraced from D to C. After the point C is reached the stress-strain curve continues along C - B, just as if the original loading had not been interrupted.

5.2.1. YIELD POINT

The yield point is the first stress in a material, usually less than the maximum attainable stress at which an increase in strain occurs without any increase in stress. Only certain metals exhibit a yield point. If there is a decrease in stress after yielding, a distinction may be made between upper and lower yield points.

5.2.2. YIELD STRESS (Earnshaw)[23]

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

(a) The load is added in equal increments, and the stress noted at which increment first causes a strain 25 per cent greater than the strain caused by that increment at the beginning of the test.

(b) The stress-strain curve is plotted as usual, and then a point is found on it corresponding to a definite plastic strain or permanent set of 0.001, i.e. of 0.1 per cent. The stress necessary to produce this permenent set of 0.1 per cent is called the 0.1 per cent proof stress. It is easily found by drawing what is called an offset line on the stress-strain curve (Figure 12). In this case the offset line starts from a strain of 0.001 and is drawn parallel to the straight line part of the stress-strain curve. The point where it intersects the stress-strain curve corresponds to a permanent set of 0.001 (or 0.1 per cent), and the stress at that point is the 0.1 per cent proof stress. Sometimes a 0.2 per cent proof stress is determined instead of 0.1 per cent, or sometimes a smaller permanent set is defined, e.g. 0.02 per cent

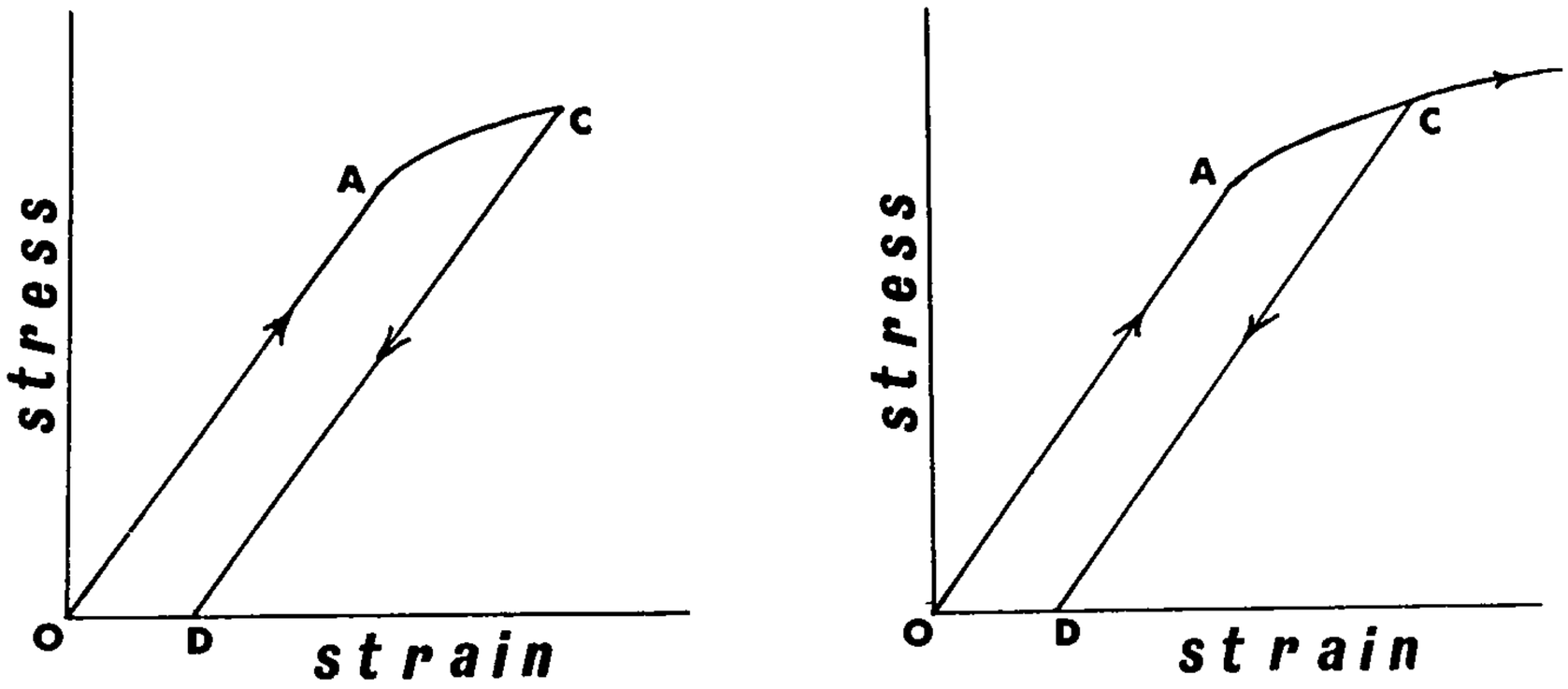


Fig. 11 - Stress-Strain Curve, Plastic Deformation.

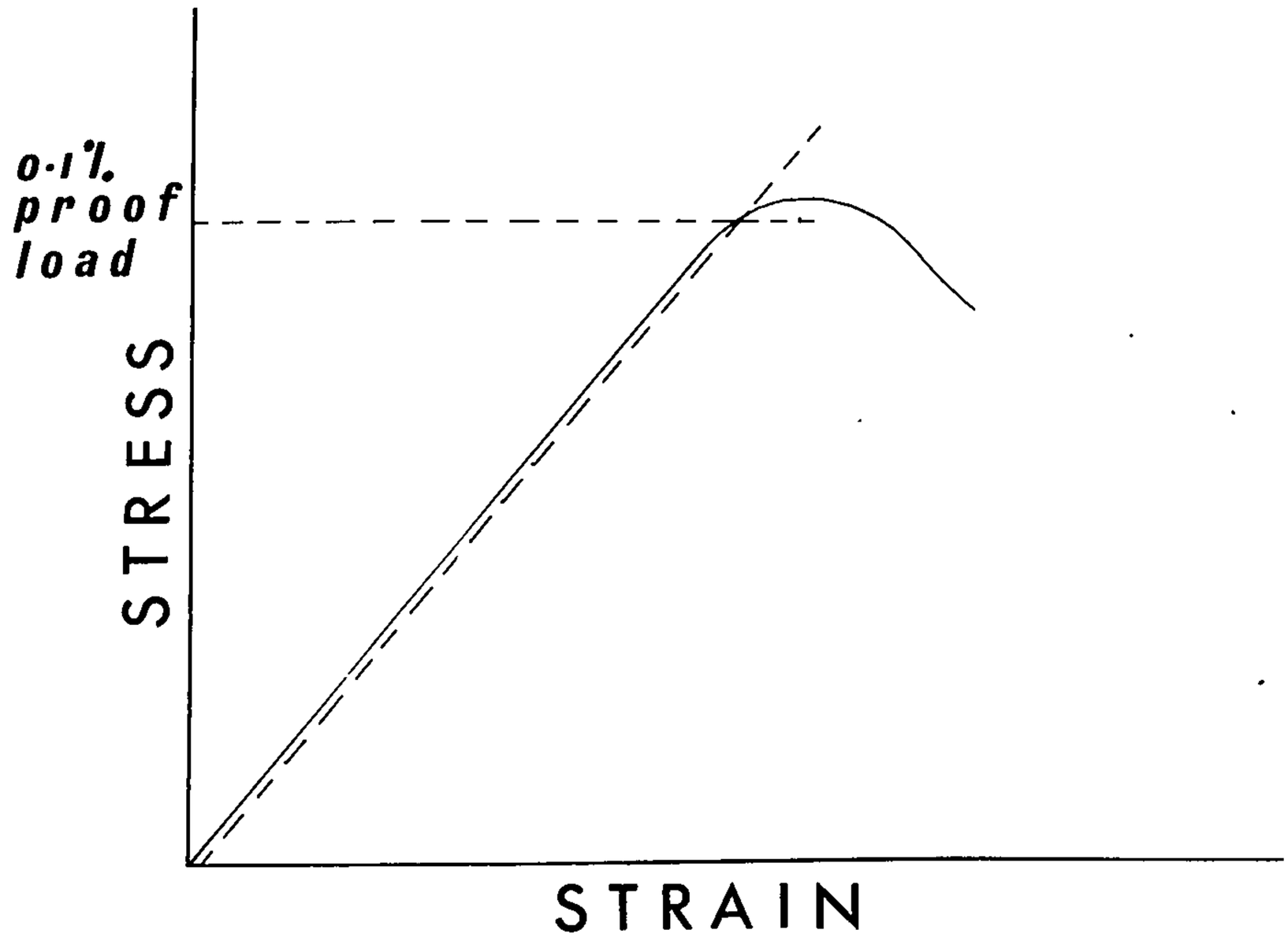


Fig. 12 - Stress-Strain Curve Proof Stress.

or even 0.01 per cent. Thus, there are two ways in which the yield stress can be measured. Both methods give similar results, since both are based on finding the stress which causes a small but easily measured plastic strain.

Yield Strength or Yield Stress

Yield strength or yield stress can be defined as the stress at which a material exhibits a specified deviation from proportionality of stress and strain. An offset of 0.2 per cent is used for many metals.

5.2.3. PROOF STRESS

Proof stress can be defined as:

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

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

5.2.4. ULTIMATE TENSILE STRENGTH

Ultimate tensile strength is the maximum conventional tensile stress that a material can withstand. In this or present evaluation it is the point at which the wire fractures.

Wilkinson[64] in his work with stainless steel wires of different diameters, and from different manufacturers found that two important points emerged from the consideration of proportional limit and tensile strength. These were:

(1) Tensile strength increases as the diameter of the wire is reduced, drawing conditions being equal.

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

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

5.2.5. DUCTILITY

Ductility is the ability of a material to deform plastically without fracturing. There are three common methods of measurement, listed by Skinner and Phillips[51]: percentage elongation after fracture, reduction in area at the fractured ends, and the cold bend test.

The most commonly used test for assessing the ductility of orthodontic wire and the one used in the present evaluation is the cold bend test. The material is clamped in a vice and bent through a pre-set angulation (see Figure 19). The number of bends before fracturing is counted, and the greater the number the greater is the ductility.

5.3. PERFORMANCE OF MATERIALS IN BENDING

Besides the usual tensile testing to evaluate the mechanical properties of the orthodontic wires under test, it is now accepted that simulated use tests be also carried out when evaluating orthodontic wires.

Orthodontic wires are subject to bending during their use in the mouth, thus it would seem that the performance of the wires under such conditions be tested.

In all forms of bending the wires may be treated as beams.

5.3.1. BEAMS (Earnshaw) [23]

A simple beam is one supported at each end, and loaded in the centre (i) Figure 9. When a simple beam bends, there will be a neutral layer where the stress is zero. This can be imagined as an infinitely thin, horizontal layer through the centre of the beam. All parts of the beam below the neutral layer will be in tension, and all parts above the neutral layer will be in compression.

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

A cantilever beam is one which is clamped at one end, and loaded at the other (ii) Figure 9. There is a neutral layer as before, and again the beam is in tension on one side of the neutral layer, and in compression on the other, and obviously shear stresses will be set up as well. A clamped or encastre beam is one which is clamped, rather than just supported at each end (iii) Figure 9. Here the bending is more complex. There is still a neutral

layer, but the stresses on each side of it change in sign from section to section of the beam.

Again, shear stresses are set up as well.

5.3.2. DEFLECTION OF BEAMS

Ware, Table 3, illustrates the three types of beam and the comparative deflections with the same load and span. The deflection D of a beam is given as $D = \frac{1}{C} \frac{L^3F}{EI}$, where F is the load, L the span, E the elastic modulus and I is a function of the shape and size of the wire. The factor C for the cantilever is 3, for the freely-supported beam 48 and for the rigid beam 192. Thus, if the three forms of beam having the same span of wire are used to exert the same force on a tooth the deflection required would be in the ratio of 64 : 4 : 1. This emphasises the discrimination required when activating mechanisms. This also highlights the difference in loading that occurs for the same deflection when a wire is loose or tight (free or rigid beams) in the brackets of the abutment teeth, this is 1 : 4. If I is substituted in the formulae for deflection where $I = \frac{\pi d^4}{64}$ for wires of diameter d and $I = \frac{WT^3}{12}$ for rectangular wires of width W and thickness T, then the formulae become $D = K \frac{L^3F}{Ed^4}$ for round wires and $D = K \frac{L^3F}{EWT^3}$ for rectangular wires. Since for round wires, the deflection required to exert a particular force will be inversely proportional to the fourth power of the diameter (d^4), it will be necessary to have a wire

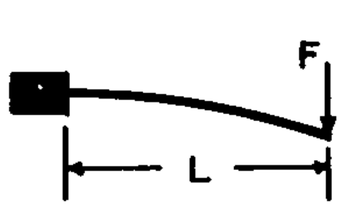
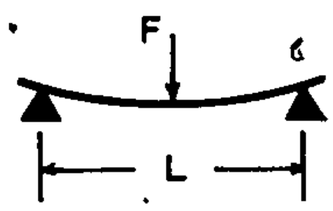
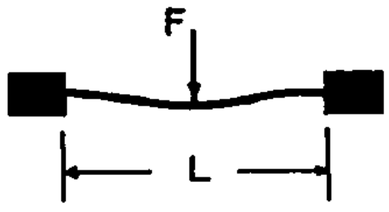
Type of Beam	CANTILEVER	FREELY SUPPORTED	RIGIDLY SUPPORTED
Form of Beam			
Deflection D	$\frac{1}{3} \cdot \frac{L^3 F}{E I}$	$\frac{1}{48} \cdot \frac{L^3 F}{E I}$	$\frac{1}{192} \cdot \frac{L^3 F}{E I}$
Ratio of deflection for the same force	64	4	1
Deflection for round wires $I = \frac{\pi d^4}{64}$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

Table 3 - The Deflection of Wires Used as Simple Beams.
(Ware, Australian Orthodontic Bulletin Jan. 1967)

of constant diameter and uniform from batch to batch in order to get consistent results.

The deflection formulae indicate, too, that only after a wide experience would it be possible to determine the qualities of wire by feel, as slight changes in dimensions can materially affect the "feel". This has also been demonstrated by supplying wires to orthodontists for determination of quality.

5.3.3. LOAD DEFLECTION RELATIONSHIP

In this present evaluation, the performance of the wires under test in bending was obtained by clamping each wire securely at one end, and progressively loading it in the form of a cantilever beam. The load is increased in small increments and the amount of deflection for each small increment in load is measured. These are plotted in a curve which closely resembles the tensile test curve (see Figure 13).

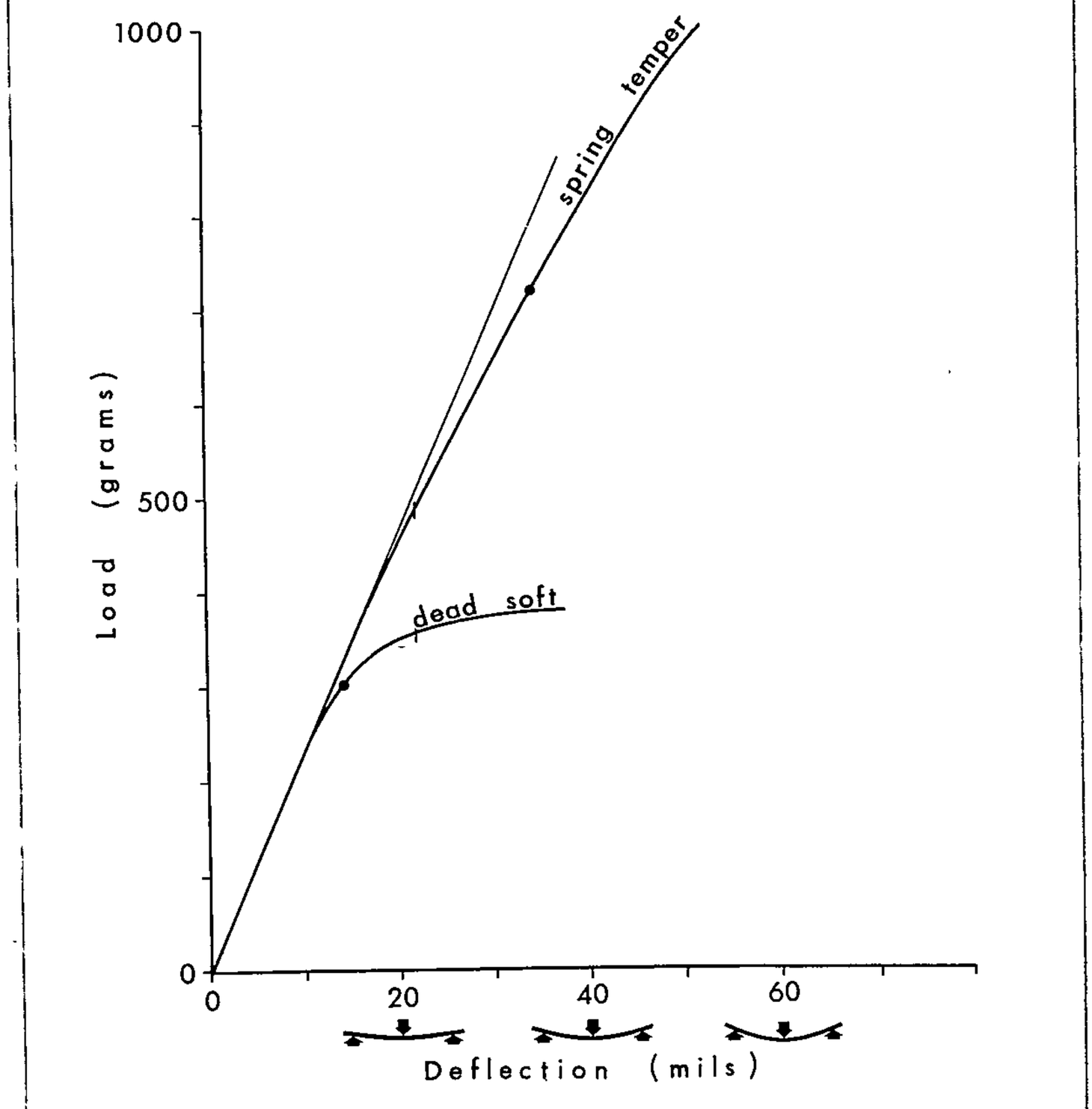
Thurow[57] gives a description of the bending test curves. The difference between a stress-bending or load deflection curve and a stress-strain curve made from a tensile test is in the region of the elastic limit and plastic deformation. In the tensile test, the entire test piece is subjected to the same strain or elongation so that the entire piece reaches the elastic limit at the same time. In bending, the outer fibres of the wire are strained (stretched or compressed) more than the inner fibres, so that these areas reach the elastic limit first.

The result of this unequal strain is that the straight-line portion of the bending curve ends when the outer fibres begin to deform plastically, even though the part near the centre is still behaving elastically and following a straight-line response. The bending curve is a composite of the response of all these fibres, therefore the transition into the upper curved portion is more gentle than it would be in the tensile test. (See Important Note later, on Assumed Elastic Limit)

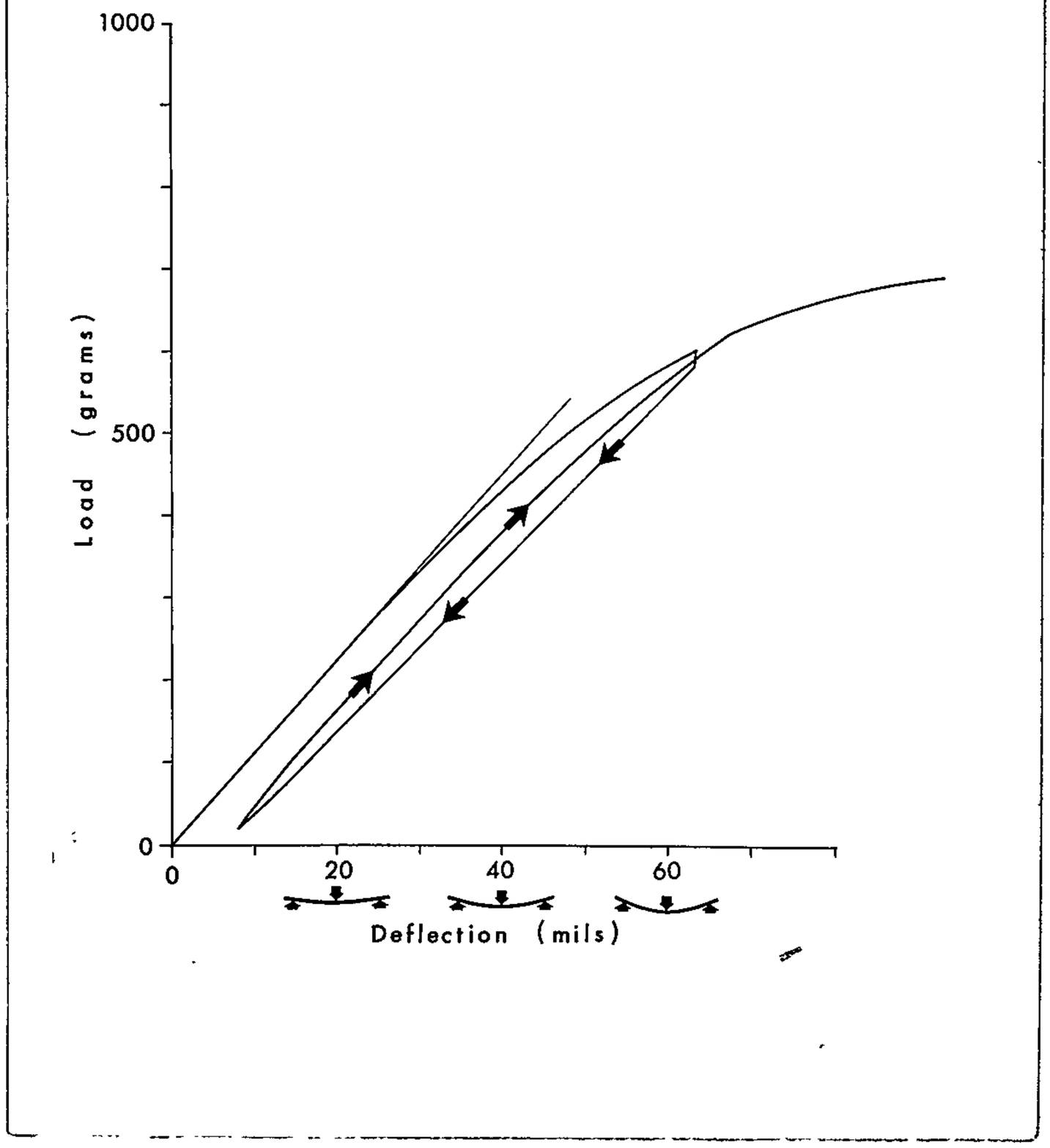
The form of the upper part of this curve is an indication of work hardening. The curve bends sharply for such metals as gold or moderately low-temper chrome-cobalt, which have undergone very little work hardening. After the elastic limit for these materials has been passed, the metal fails under a relatively small additional force. Stainless steel has been heavily work hardened in drawing, and the result is a higher and more gentle curve as the wire resists much greater maximum loads (Figure 13).

It can be seen from the curves that stainless steel has a high reserve strength beyond the elastic range as a result of this work-hardening effect. This is a great advantage in wires with small diameters, but it can be a distinct disadvantage in wires of larger size.

Releasing the load from a wire in the plastic range results in a curve such as the descending line shown in Figure 14. This more or less straight line shows slight curves at the upper and lower



[Fig. 13 - Effect of hardness or temper on the bending properties of stainless steel. Curves show 20-mil wires, dead-soft and hard-drawn spring temper. Stiffness is identical. Working range and strength are much higher for the hard wire. (Thurow)]



[Fig. 14 - Effect of unloading and reloading a bending wire beyond the elastic limit. (Thurow)]

ends. On reloading, the curve ascends almost parallel to the original loading and unloading lines, but between them. The "hysteresis loop" formed by the unloading and reloading curves represents energy lost to internal friction in the wire and dissipated as heat. As the reloading curve reaches the original curve, it continues in an extension of that curve, following the same line that it would have followed without the interruption.

Because the stress-bending curve represents actual response of a wire under clinical stresses, it gives information that can be directly adapted to clinical practice.

Note: The value obtained for the elastic limit in bending, should be referred to as the Assumed Elastic Limit.

From the section on load deflection relationship (5.3.3.) it will have been noted that in bending, the outer fibres are stretched initially while further in there is a neutral zone and on the inner curve the fibres are in compression.

What is recorded during the bend test, as the elastic limit on the load-deflection curve, is not, as Thurow states, the point where the outer most fibre has just begun to deform plastically. It is rather the point where the outer fibres have been stretched to the stage of plastic deformation and this plastic deformation has advanced inwardly through the wire until such a stage that enough of the wire was so effected that the inner neutral and compressed layers could no longer support the outer plastically

deformed fibres and the wire then begins to fail. This point is far past the true elastic limit, and is referred to as the assumed elastic limit (assumed elastic limit is represented in theoretical formulae by the notation Smax).

Henceforth, any reference to elastic limit in bending will be taken as referring to the assumed elastic limit.

Formulae Pertaining to the Calculation of:

(1) Stress at the assumed elastic limit;

(2) The modulus of elasticity in bending.

The formulae used in these calculations were taken from Braddick[15]. They are commonly used formulae and can be found in many textbooks.

(1) Stress at the assumed elastic limit

If stress at the assumed elastic limit be represented by Smax

$$\text{Then } Smax = \frac{P\ l\ r}{I}$$

Where P = load

l = length

r = radius

I = a constant - for a cantilever beam $I = \frac{\pi d^4}{64}$

Substituting $\frac{\pi d^4}{64}$ for I

and $\frac{d}{2}$ for r where d = diameter

$$\text{Then } S_{max} = \frac{64\ P\ l\ d}{2\pi d^4}$$

$$= \frac{32\ P\ l}{\pi d^3} \qquad \ldots\ldots (7)$$

(2) Modulus of elasticity in bending

The formula for modulus of elasticity is developed from the formula for deflection.

If deflection be represented by d_f

$$\text{Then } d_f = \frac{P\ l^3}{3\ E\ I}$$

Where P = load

l = length

E = modulus of elasticity

I = a constant - for a cantilever $I = \frac{\pi r^4}{4}$

Transposing E

$$E = \frac{P\ l^3}{3\ d_f\ I}$$

Substituting $\frac{d}{2}$ for r in equation $I = \frac{\pi r^4}{4}$

Where d = diameter

$$\text{Then } I = \frac{\pi d^4}{64}$$

Now substituting for I

$$E = \frac{64P\ l^3}{3\pi\ d_f\ d^4} \qquad \ldots\ldots (8)$$

5.3.4. FLEXIBILITY OF STRUCTURE

The flexibility of structure is the amount of distortion, of any given character, which the structure undergoes when a load within its elastic strength is applied to it (Brumfield) [17].

The term is usually reserved for distortion due to bending. Flexibility depends on the physical properties of the materials of which the structure is fashioned and on the general form and detailed dimensions. The two properties of materials which are pertinent to the flexibility of all structures are proportional limit and modulus of elasticity. The higher the proportional limit the greater the flexibility under given conditions. Inversely, the higher the modulus of elasticity the less the flexibility, other conditions being constant. The flexibilities of most orthodontic structures are in the main required under conditions which bring bending forces to bear on the structural parts. The general law of flexibility in bending is

$$y = K \frac{f_p L^2}{Ev} \qquad \ldots\ldots (9)$$

where y is the flexibility of the structure

f_p is the proportional limit of the material

L, the length of the structure under bending

v, the depth of the structure (for symmetrical sections) in the plane in which bending occurs. The values of "v" may be constant or variable depending on conditions.

K is constant for any given structure. It reflects the type of loading, and type and manner of supports at the ends of the beams. In the case of a cantilever beam, with a single concentrated load at the end K is 1/3. For more complicated structures, the value

of K may be difficult to determine. Nevertheless the equation is useful for comparative purposes. If it is desired to make a comparison of the possible flexibilities of two structures from different materials, but in identical structural forms, the value of K, whatever it may be, will cancel and the physical properties of the materials become the determining factors in making the comparisons. Such comparisons are of value for semi-design purposes.

Special Note on Resiliency

Brumfield[17] makes special reference to resiliency in his book, stating that what has been referred to as resiliency in a wire by orthodontists should in effect be referred to as flexibility.

Resilience from section 5.1.8. is a measure of strain energy in tensile, where as flexibility is the term usually reserved for distortion due to bending (Brumfield)[17].

Thus in evaluating the wires under test the value obtained for flexibility will be of major importance. But by the same token the variables involved in the calculation of this value for flexibility create quite a complex situation.

CHAPTER 6

AIMS AND OBJECTIVES OF PRESENT EVALUATION

The aims of this project were to carry out tensile ductility and bending tests on selected .016 inch diameter round wires. From these tests it was intended to evaluate the mechanical properties of the wires with regard to specific features which would be essential for a wire suitable for use in the fabrication of archwires for treatments involving the Australian (Begg) Light Wire Technique. Previously from Chapter 2 it will have been noted that three of the essential features of a wire suitable for use in the Australian (Begg) Light Wire Technique are that it be:

(1) Highly resilient in accordance with Australian Standard T32.

(2) Highly flexible to avoid distortion during mastication.

(3) Sufficiently ductile to allow the auxiliaries to be bent into the archwire without fracture.

In order to compare the various wires, mechanical tests were chosen which would show their properties with regard to the above three points. It was therefore decided to examine the wires for the following mechanical properties:

Tensile Tests

(a) Ultimate Tensile Strength (U.T.S.)

(b) Proportional Limit

(c) 0.02 per cent Proof Stress

(d) Young's Modulus of Elasticity

Ductility Tests

(e) Maximum Ductility

Bend Tests

(f) Elastic Limit in Bending

(g) Modulus of Elasticity in Bending

(h) Flexibility

A value for (h) Flexibility was calculated from tensile and bend test figures.

CHAPTER 7

7. MATERIALS AND METHOD

7.1. MATERIALS

7.1.1. WIRES TESTED

The wires tested were listed in the Introduction, but in order to refresh the reader's memory, they were:

(1) Various grades of Wilcock Wire, known in overseas orthodontic circles as "Australian Wire", "Special Plus", "Special", "Regular Plus" and "Regular".

(2) Dentaurum Remanit, "Super Spring Hard". Marketed in U.S.A. as "Boomerang Wire".

(3) "Unisil".

(4) "Red Elgiloy" (Cobalt Nickel Alloy).

All wires tested were nominally .016 inch diameter. Four coils of each type of wire to be tested were selected, except in the case of "Red Elgiloy" which is supplied in straight lengths of 15 inches and comes packaged in 30 lengths per package.

All wires were used in the as-received condition, the exception again being "Red Elgiloy" which was heat-treated in a furnace for seven minutes at 482°C (900°F) in accordance with the manufacturer's specification.

7.1.2. TENSILE TESTING EQUIPMENT

A Hounsfield Tensometer, Type W (Figure 15), was used to carry out the tensile tests on the various wires. The chucks used to hold the wires were vee-wire grips, listed in the Hounsfield Instruction Manual as part 184d (Figure 18). The extensometers used were a matched set No. 701, 702 of Huggenberger Tensometers, Type E, with a factor of 1,000 (Figures 16 and 17).

7.1.3. DUCTILITY TESTING EQUIPMENT

The ductility tests were carried out with apparatus made at the Dental Materials Laboratory, Dental School, Sydney, and shown in Figure 19. It consisted of a clamping device to hold the wire in position attached to a metal backing plate in which had been placed two pins offset at 40° from the perpendicular to allow for the wire under test, when clamped in position and held by a pin vice .036 inch clear of the clamping unit, to be bent from side to side through a total distance of 80°. This apparatus was constructed to comply with Australian Standard T32 for ductility testing by cold bend test.

7.1.4. BENDING TEST EQUIPMENT

The testing apparatus was also constructed at the Dental Materials Laboratory, Dental School, Sydney (Figure 20). It consisted of a simple clamping device suspended between two solid aluminium columns.

Hounsfield Tensometer

Type W

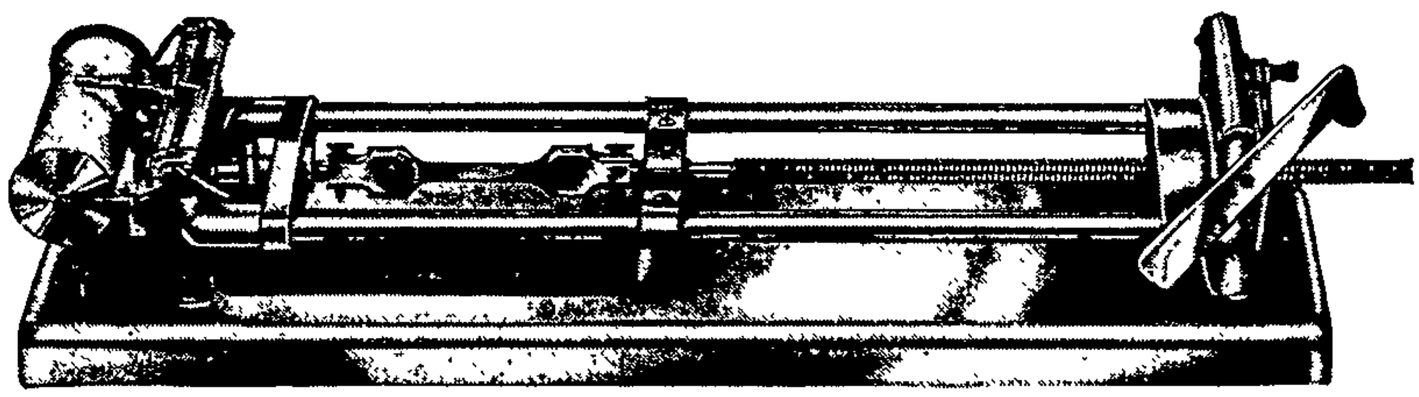


Fig. 15 - Hounsfield Tensometer Type W.

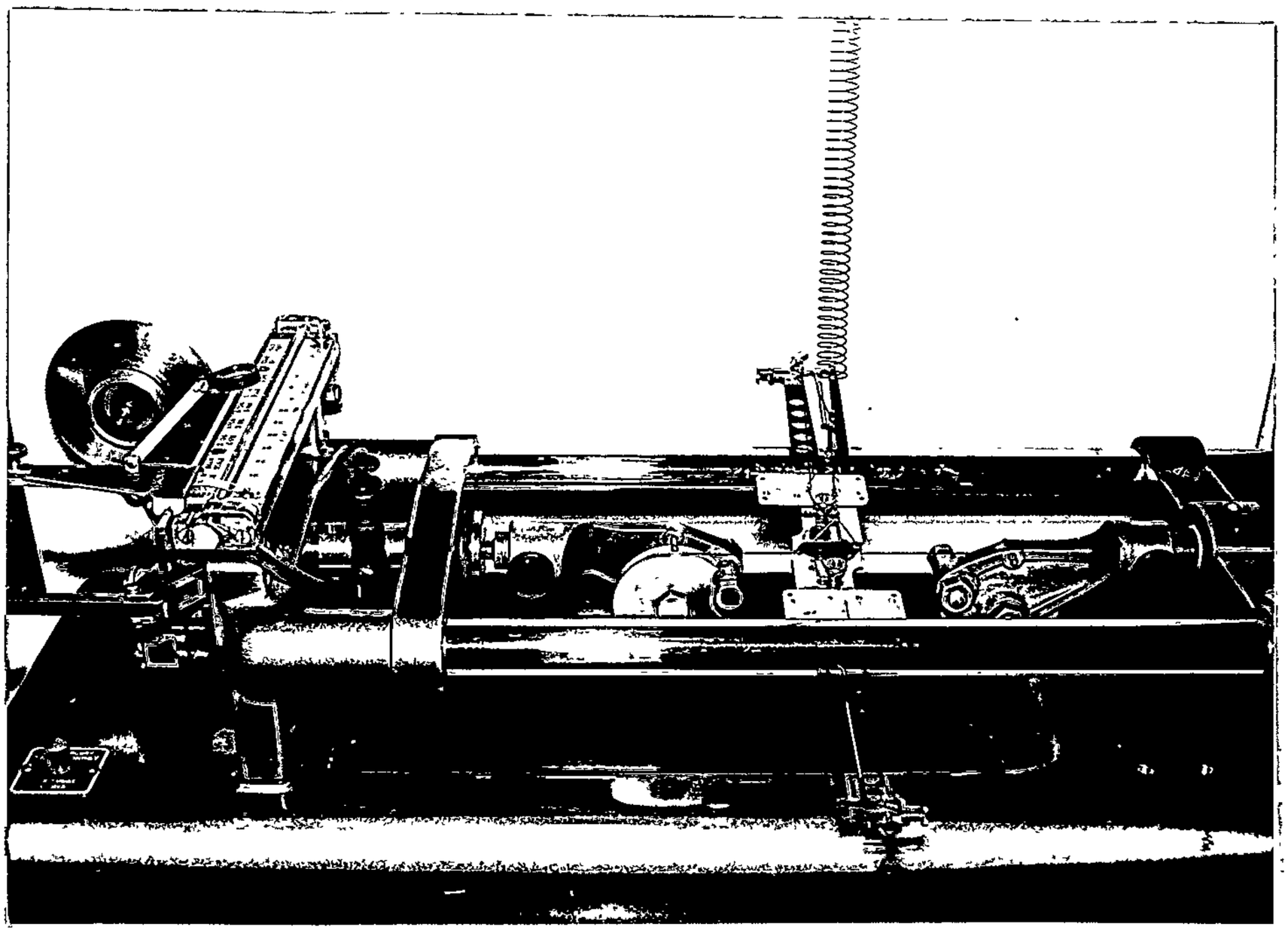


Fig. 16 - Illustrating Apparatus Set Up for Testing and showing Coil Spring to Counter-balance the Huggenberger Extensometers.

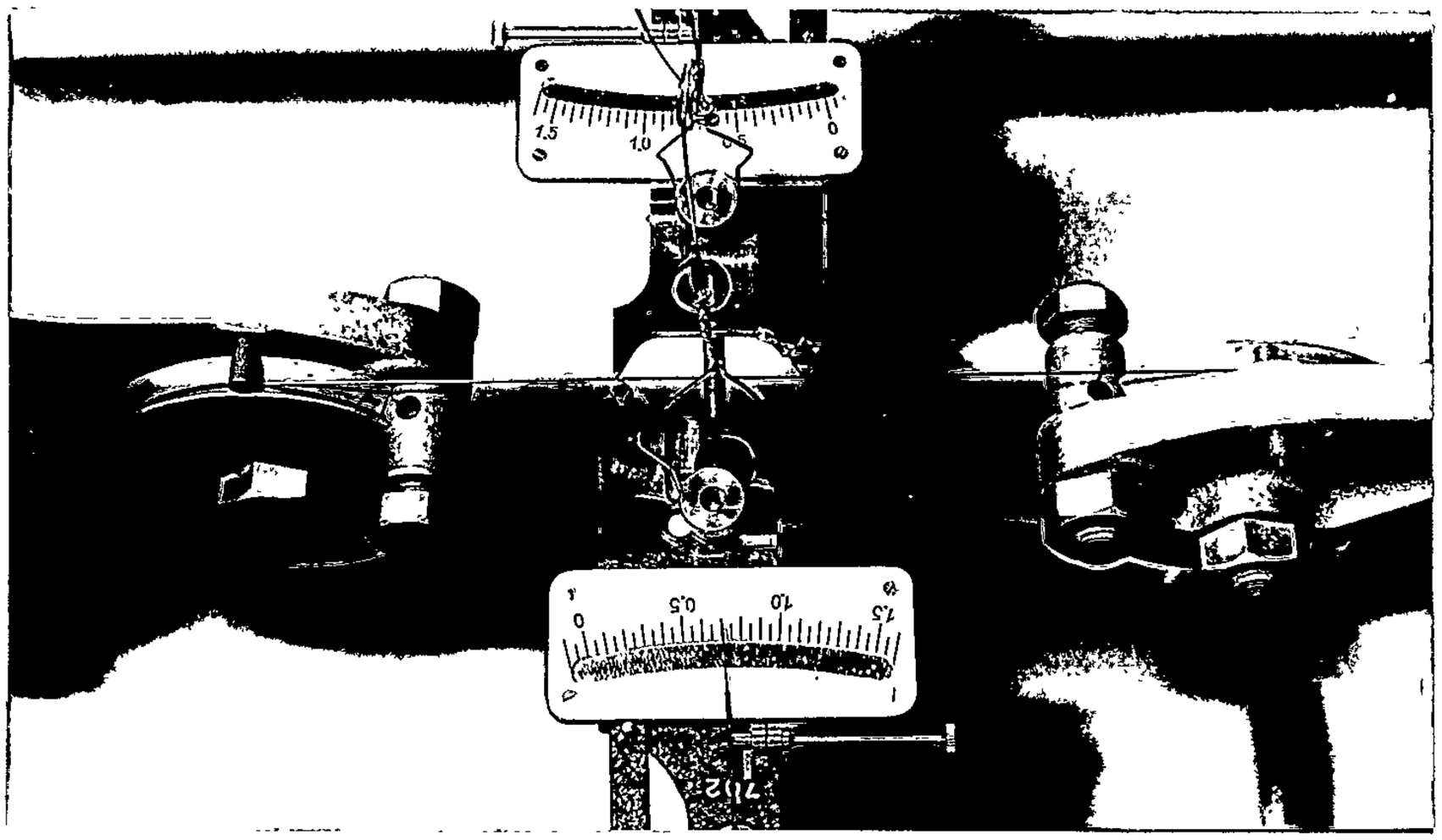


Fig. 17 - Close-up of Vee-Wire Grips and Huggenberger Extensometers.

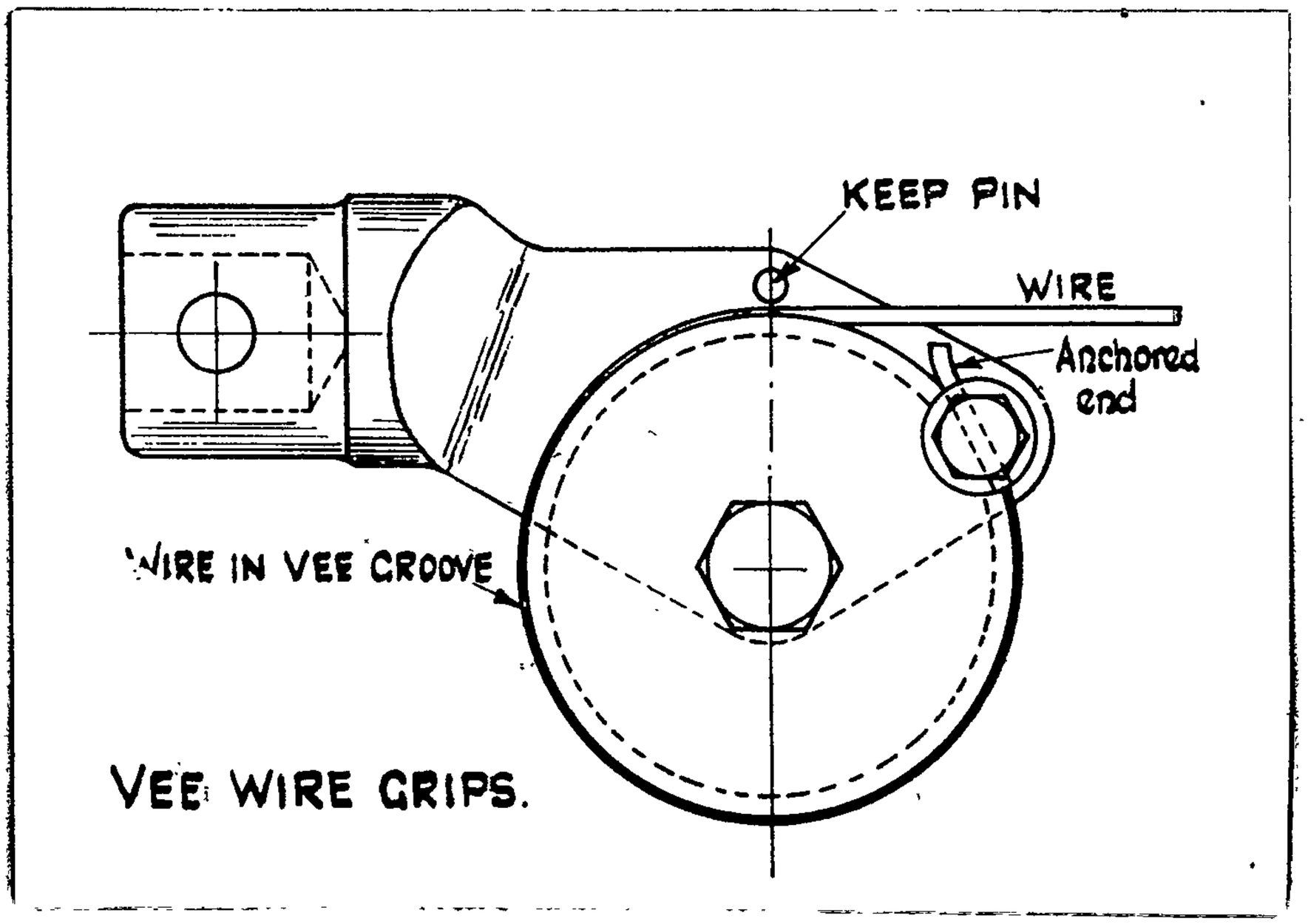


Fig. 18 - Vee-Wire Grips.

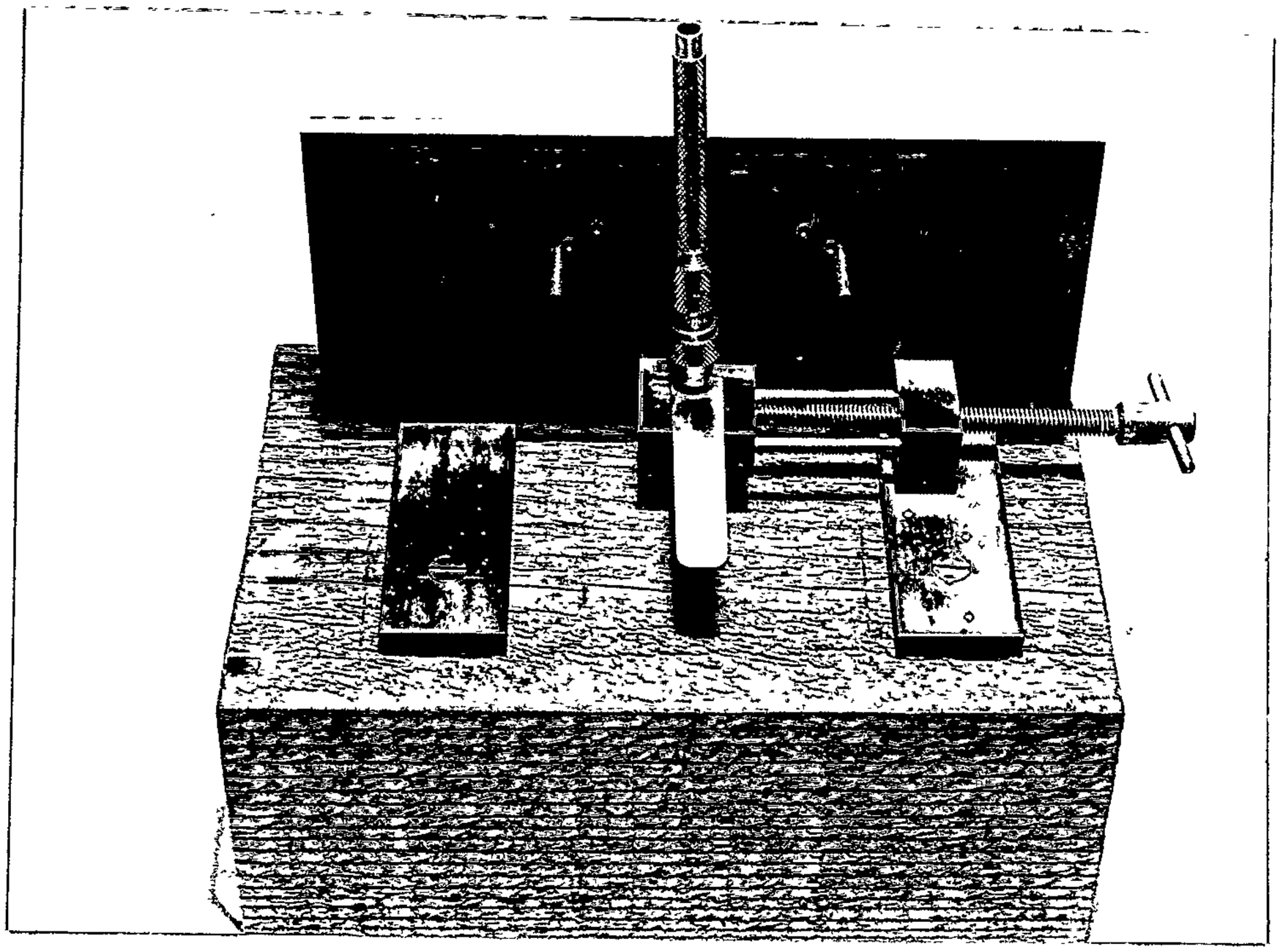


Fig. 19 - Ductility Testing Apparatus (Cold Bend Test)

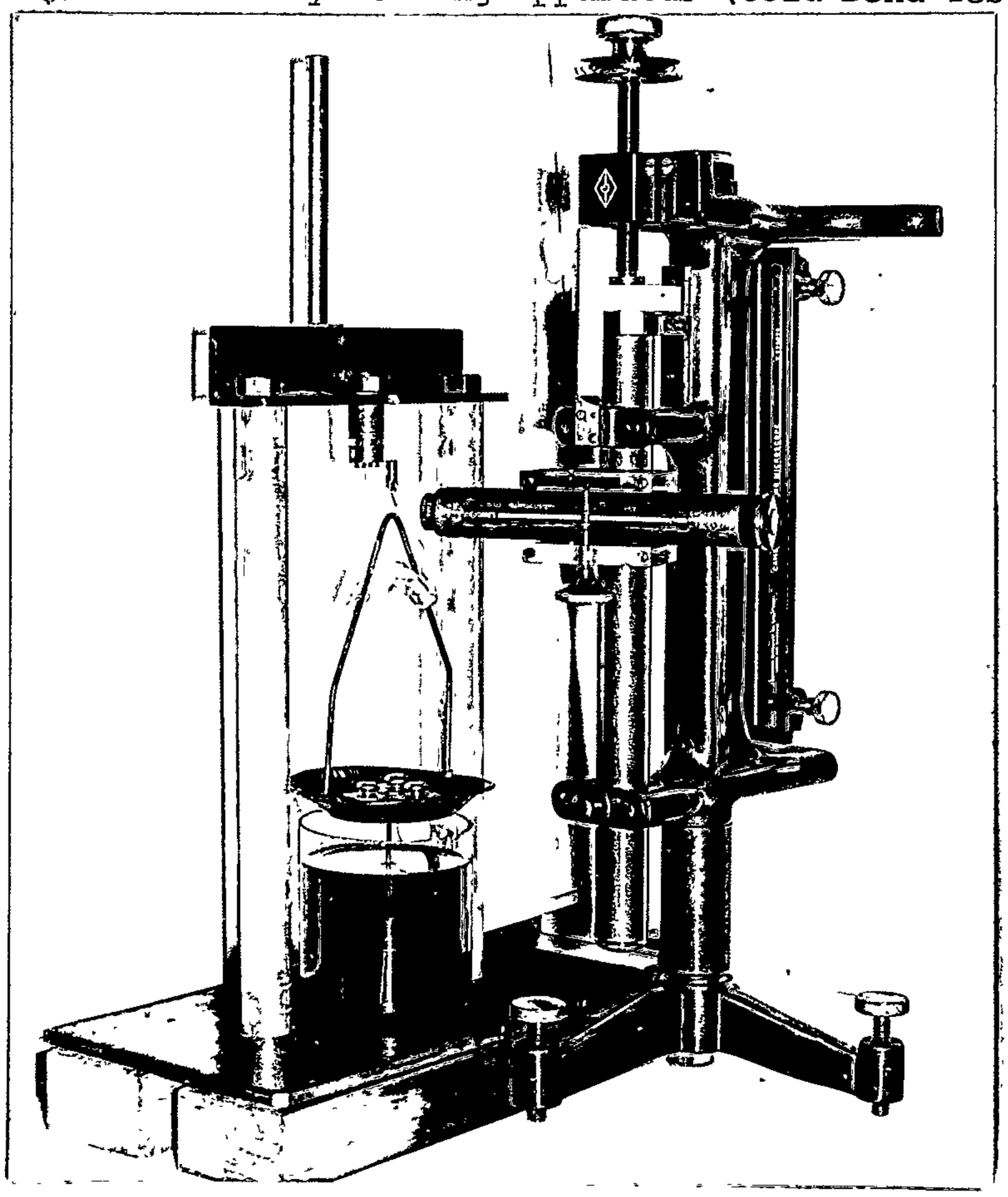


Fig. 20 - Apparatus for Bend Testing

Two brass discs with fine opposing grooves in each disc, provided the clamping mechanism. This allowed a wire to be slipped between the discs and the discs tightened up by use of two screws passing through the discs. This held the wires firmly in position. The metal tray on which the load increments were placed, had a damping device added to reduce the vibration. This consisted of a framework of wire extending from the base of the tray into a beaker of oil. A Cambridge Cathetometer was used to measure the deflection after each increment in load.

7.1.5. EQUIPMENT FOR MEASURING DIAMETER OF WIRE

The wire diameter was measured along each length of wire after it was cut from the coil, with a Micrometer which measured to .0001 of an inch.

7.1.6. CALCULATING MACHINE

All calculations were completed on a Monroe Epic 3000 Calculating Machine.

7.2. METHOD

This project was divided into two sections:

(a) Tensile Testing and Ductility estimations were carried out on all wires.

(b) Bending tests were carried out only on wires which obtained a high Type C or Type D classification according to Australian Standard T32 and had satisfied the ductility requirements.

7.2.1. TENSILE TESTING

Hounsfield Tensometer

The Hounsfield Tensometer was checked before each testing. The end plate used was 125 pounds, the scale which corresponded with the end plate was fitted and it was scaled from 0 to 120 pounds in scaled increments of 1 pound. The mercury was then adjusted to zero.

7.2.2. VEE GRIPS

The ideal length of wire for testing was about 15 inches. This allowed sufficient to wrap around the vee grips and still allow about 4 inches of wire between the chucks on which to attach the extensometers.

The wire was held firmly by firstly clamping the end of each wire by means of a screw tightened on the wire in each vee grip then coiling the wire around the grip and using the friction for further support (see Figure 18).

From the already selected coils a 15 inch length of wire was cut and fitted into the chucks, the chucks in turn were then pinned into the testing machine.

The Hounsfield was then hand wound till the wire under test was under 20 pounds of load. At this stage the wire was free from kinks and firmly under tension. It was now time to fit the Huggenberger extensometers.

7.2.3. FITTING THE HUGGENBERGER EXTENSOMETERS

(A special note on fitting these extensometers on such very fine wire.)

The Huggenberger Type E extensometers used are made for use on fine wires, but perhaps they have not been used on wire as fine as .016 inch. All the accepted methods of using a special shoe to fit the wire to one set of the extensometers then adjust the other to it were not very successful.

The method which I found to be most satisfactory was to place the extensometers in position from under the wire, hold the teeth of one of the opposing extensometers hard on the wire and then with the help of an assistant wind up the double clamping device which holds the extensometer firmly together on the wire. This has made it all sound very easy; there were many times that after all this procedure the extensometers would slip half way through a set of readings and it was back to a new length of wire and start again.

7.2.4. COUNTER-BALANCING THE EXTENSOMETERS

In order to reduce the weight of the extensometers on the wire under test, a coiled spring was suspended from a clamp above the extensometers and attached to the extensometers and adjusted so that with the extensometers in position on the wire they were almost weightless.

7.2.5. TAKING OF READINGS

With the extensometers set at zero and the safety holding device turned clear from the arms we were now ready to proceed. The load was increased in 5 pound increments up to 30 pounds and each time the extension was read and noted. When the pointer had travelled across the dial from 0 to 1.6 it was turned back to zero and you could continue on. Once at 30 pounds the load was increased only by 2 pound increments, and each time a reading was taken.

Before the wire reached its breaking point, or when the extensometers came to the end of their range, the extensometers were removed. The wire was then loaded till it broke. This value was read from the scale at the end of the machine. From this value it was simple to calculate the value for the ultimate tensile strength by dividing the load by the area of the wire:

$$\text{U.T.S.} = \frac{\text{Max. Load}}{\text{Area}}$$

7.2.6. PLOTTING THE STRESS-STRAIN CURVE

With the readings obtained from the test a graph of stress against strain was plotted.

The line of best fit was drawn through the points plotted on the graph in order to establish the linear portion of the stress-strain curve and give us the elastic range of the material.

This line was continued in either direction till it cut the upper and lower limits of the graph. The values for extension and

stress where it cuts the margins of the graph were noted, as they were necessary for determination of the modulus of elasticity.

7.2.7. VALUES OBTAINED FROM THE STRESS-STRAIN CURVE

The point at which the straight line portion ceases and the stress-strain curve begins to dip away was noted. Up to this point the wire had been obeying Hooke's Law and behaving elastically. Thus the uppermost point on the straight line portion of this graph is the point of the proportional limit.

The exact position of where this line first begins to deviate from the straight line is often difficult to estimate. A more positive value is that obtained for the proof stress.

From definitions 5.2.2. and 5.2.3., there are two methods of determining the yield stress. In this case I chose to determine a 0.02 per cent proof stress, as from the figures obtained from the tests, it could be seen that a 0.02 per cent proof stress was equivalent to about a 25 per cent increase in strain. The advantage of using 0.02 per cent proof stress is that it is a definite point where an offset line drawn through 0.0002 inch and drawn parallel to the straight portion of the stress-strain curve, cuts the stress-strain curve. The value obtained at that point is the yield stress for a 0.02 per cent proof stress.

Note: Proof stress is a definite point on the stress-strain curve, whereas proportional limit estimations may vary from operator to operator.

Modulus of Elasticity or Young's Modulus (Definition 5.1.7.)

As already noted the straight line portion of the stress-strain curve has been extended to upper and lower levels and readings at these points have been noted. Now this line may be given co-ordinates x and y. The upper end $^{x}2$ and $^{y}2$ and the lower end co-ordinates are $^{x}1$ and $^{y}1$. Now the slope of the line may be expressed as:

$$\text{Slope} = \frac{y_2 - y_1}{x_2 - x_1}$$

By substituting values obtained from stress-strain graph for these co-ordinates, a value for Young's Modulus of Elasticity can be easily calculated.

7.3. DUCTILITY

A piece of wire about 1 inch in length was cut from the coil to be tested. About half the length was fitted into the pin vice, the end projecting from the pin vice was inserted perpendicularly into the jaws of the clamping unit. The distance between the end of the pin vice and the clamping unit was kept at .036 inches as recommended in Appendix D of Australian Standard T32, by use of a brass feeler strip.

The wire was held vertically, bent firstly to the right through 40°, then back through 80° then back 40° to the vertical. This completed one cycle. The bending was continued till fracture occurred. This value gave maximum ductility.

7.4. BENDING TESTS

When the tensile testing and ductility estimation were complete, wires were selected which had been classified High Type C or Type D and had satisfied the ductility requirements from the previous testing. They were Wilcock "Special Plus" classified Type C and "Unisil" classified Type D.

It was decided to carry out a comparative load-deflection bend test. A length of wire about 1.5 inches long was cut from the test coil. The piece of wire was then straightened, at a point $\frac{1}{4}$ inch from one end the wire was bent 75°. A fine cutting disc was then used to place a groove in the inner curve of this bend. The wire was then placed in the clamping device already described, the distance from the groove to the brass discs used for clamping was measured and in all tests kept at $\frac{1}{2}$ an inch. This distance was measured by using a piece of brass rod cut down to $\frac{1}{2}$ an inch which could be fitted between the edge of the brass disc clamping unit and the groove in the wire.

The aim was to find the elastic limit of the wire in bending. Loads starting from 100 gms. were placed on the wire by means of a metal tray attached to the wire by the edge of a razor blade which sat in the groove in the wire. This tray had a damping device fitted to cut down the vibration after each loading (see Materials).

The loads were added in increments of 50 gms. till 200 gms. load was reached. From then the load was increased in increments of 10 gms. For each loading the deflection was read using the Cambridge Cathetometer. The last reading was taken when it became obvious that the proof load had been exceeded.

The values obtained for load and deflection were plotted. From the resulting load deflection curve values for elastic limit and modulus of elasticity in bending were determined.

7.5. CALCULATION OF FLEXIBILITY

Values for flexibility of "Unisil" and Wilcock "Special Plus" were calculated from figures obtained from both tensile and bend tests, by applying equation (9)

$$y = K \frac{f_p L^2}{Ev}$$

(1) Tensile Test

Values obtained for proof stress and Young's Modulus of Elasticity were substituted to derive a value for flexibility from the tensile tests.

(2) Bend Test

Values obtained for elastic limit and modulus of elasticity in bending were substituted in order to arrive at a figure for flexibility in bending.

CHAPTER 8

8. FINDINGS AND DISCUSSION

All results from this evaluation have been tabulated and are contained in Tables 4, 5, 6, 7, 8, 9 and 10. Typical tensile and bend test curves obtained for various wires tested are shown in Figures 21, 22 and 23.

In this Chapter it is intended to analyse these tables, pick out the significant findings and discuss their implications for each particular test. Finally the overall result that emerges when the findings of all the various tests are combined will be assessed.

8.1. DIAMETERS OF WIRES

The diameter of the various wires tested are shown in Table 4. The value quoted for each wire is the mean value obtained for each batch of wire under test.

All wires came within the allowable tolerance stated by Australian Standard T32. This tolerance is $\pm$ 0.0005 of an inch.

In all calculations involving the determination of the properties of the wires the individual value for the diameter of the specific length of wire under test was used.

8.2. DUCTILITY

Table 4 also contains the values obtained for ductility. All wires gave satisfactory results with the exception of "Red Elgiloy"

(heat-treated) which was completely non-ductile to such an extent that it was not even possible to complete one movement of the wire through 40° before it fractured.

An interesting point arising from the ductility test was that Dentaurum Remanit "Super Spring Hard", regarded amongst orthodontists as a "reliable wire" and advertised in the U.S.A. under the "Boomerang" trademark as "It's Less Brittle and we guarantee it", came up with the lowest ductility rating, except for the non-ductile "Red Elgiloy".

Both "Unisil" and Wilcock "Special Plus" had very similar ductility. The lowest in the Wilcock range "Regular" was not as ductile as "Special" or "Regular Plus".

TABLE 4

Values Obtained for Diameter and Ductility

Material	Diameter (ins.)	Maximum Ductility Number of Bends Till Fracture	
		Mean	S.D.
Wilcock Special Plus	.0162	24	1.0
Wilcock Special	.0160	29	1.0
Wilcock Regular Plus	.0162	32	2.0
Wilcock Regular	.0160	28	1.0
Dentaurum Remanit Super Spring Hard	.0155	23	2.0
Unisil	.0160	25	2.0
Red Elgiloy (Heat Treated) 482°C	.0156	Nil	-

8.3. TENSILE TESTING

8.3.1. ULTIMATE TENSILE STRENGTH

Table 5 contains the result obtained for ultimate tensile strength (U.T.S.) and the subsequent classification in accordance with Australian Standard T32.

"Unisil" wire had the highest U.T.S. of the wires tested and was the only wire to achieve a Type D classification.

Wilcock "Special Plus", which had previously been certified Type D by the Commonwealth Bureau of Dental Standards, produced an U.T.S. of only 380,000 pounds per square inch which placed it in a Type C classification.

Wilcock "Special" showed an U.T.S. of 371,000 pounds per square inch which place it on the minimum value for certification as a Type C wire.

Wilcock "Regular Plus" produced a satisfactory result in line with its previous certification, being well within the limit for a Type B wire.

Once again however, the value for the U.T.S. of Wilcock "Regular" was only 304,000 pounds per square inch which placed it in a Type A classification where previously it had been certified Type B.

Appreciating the implications of these findings with regard to the Wilcock range of wires, it was decided to carry out a random

test on various batches of Wilcock "Special Plus" obtained from various orthodontic practices throughout Sydney. It was also decided to re-import "Australian Wire" from T.P. Laboratories La Porte, Indiana, U.S.A. The results of these tests are contained in Table 10. It will be noted from this Table that only one batch B.ROL proved to be up to specifications for a Type D wire (more will be said later on this point).

The heat-treated "Red Elgiloy" gave the second highest reading of the wires tested, with a value of 386,000 pounds per square inch.

Dentaurum Remanit "Super Spring Hard" gave a value in accordance with its previous certification Type B.

TABLE 5

Values obtained for Ultimate Tensile Strength and subsequent Type Classification in accordance with Australian Standard T32.

Material	U.T.S. (1000 lbs/sq. in.)		Classification Findings Present Evaluation	Previous Certified Classification
	Mean	S.D.		
Wilcock Special Plus	380	1.9	Type C	Type D
Wilcock Special	371	5.5	Low Type C	Type C
Wilcock Regular Plus	354	2.2	Type B	Type B
Wilcock Regular	304	3.7	Type A	Type B
Dentaurum Remanit Super Spring Hard	352	5.3	Type B	Type B
Unisil	404	2.5	Type D	Not as yet Certified
Red Elgiloy (Heat Treated) 482°C	386	2.6	Type C	Certified Type A non heat-treated

8.3.2. PROPORTIONAL LIMIT AND PROOF STRESS

From Table 6 it will be noted that "Unisil" wire had the highest value for proportional limit and proof stress of all the wires tested.

The wire with the second highest value for proportional limit and proof stress was Remanit Dentaurum "Super Spring Hard" wire.

"Red Elgiloy" (heat-treated) had a slightly higher value for proportional limit and proof stress than did Wilcock "Special Plus".

The other Wilcock wires followed in order as would be expected.

Discussion

The reader may ask, "Why record the value for proportional limit and proof stress, why not one or the other?"

The author would answer this by first stating the problems that confronted him when he was reviewing the previous comparative work done on archwire material.

Researchers who had reported their findings on the elastic properties of various archwire materials had used the terms, elastic limit, proportional limit and yield strength. Each researcher in turn would have his own particular thoughts and interpretation on just where on the stress-strain curve he would select the point which would give the value he required for the elasticity of the material. Basically all these points are

concerned with estimating where the stress-strain curve ceases to behave linearly and begins to curve away. If one looks at any stress-strain curve, there is always a range from which one might select the point where linearity ceases. No doubt each operator on each project has his own method of selecting the point where linearity ceases, and would apply it equally to all stress-strain curves in the one comparison. Another man given the same graphs may select points completely different to those selected by the previous operator, for reasons previously stated. Thus it can be seen, that comparison of the findings from various researchers who have used values such as proportional limit, should be approached with some caution.

In this evaluation therefore the author decided to use a value for .02 per cent proof stress, which be definition 5.2.2. and 5.2.3., is a definite fixed point on the stress-strain curve (see Figure 12).

The reason for recording the values for proportional limit and .02 per cent proof stress therefore was to show that the value for .02 per cent proof stress is so little above that of the proportional limit; but, being one point only on the stress-strain curve, its value could be taken as a positive finding and would allow better comparison of one researcher's work with another.

It is only by pooling the findings of various researchers that we can hope to expand our knowledge on wires. These findings can

only be pooled if they have been expressed in a standard form which is both reliable and acceptable to all.

In view of what has been stated by the author, the value for .02 per cent proof stress will be used in all comparisons of elastic properties of the materials tested in this project. The values for .02 per cent proof stress will be substituted for proportional limit in all calculations. This proof stress value is often referred to as the maximum elastic limit.

A good example of the use of proof stress values for comparison between the work of different researchers can be seen if one looks at the work of Craig et al (1965) [19] and compares it with the present evaluation.

Craig et al had carried out tensile tests on heat-treated 17-7 semi-austenitic stainless steel light wire. The figures obtained were yield strength (proof stress) 315,000 pounds per square inch and U.T.S. 355,000 pounds per square inch. In the present evaluation, Dentaurum Remanit "Super Spring Hard", a heat-treated 17-7 precipitation-hardening stainless steel had a .02 per cent proof stress of 295,000 pounds per square inch and a U.T.S. of 354,000 pounds per square inch.

Now by comparing the figures of both evaluations we find that the U.T.S.'s are identical and that the proof stress values compare favourably.

This, in the author's mind, besides confirming the figures on the present evaluation, also points to the accuracy of the testing undertaken on this and the other wires.

With regard to "Red Elgiloy" and Wilcock "Special Plus", the figures for .02 per cent proof stress and U.T.S. in the present evaluation show similar results to those of Mutchler[40] in that the value for .02 per cent proof stress for "Red Elgiloy" (286,000 pounds per square inch) was slightly better than that obtained for Wilcock "Special Plus" (281,000 pounds per square inch). Mutchler had compared the proportional limits of the two wires.

However, in this present evaluation the author found "Red Elgiloy", when heat-treated, extremely difficult to handle. It was so brittle that, when the screw on the vee grips used to hold the wire for tensile testing was tightened on the wire, it fractured. This could only be overcome by annealing the ends of the wire that fitted into the screw hole in the vee grips.

Whereas Mutchler recommended "Red Elgiloy" as being satisfactory for use in the Australian (Begg) Light Wire Technique, the author of this present evaluation would recommend against its use. This is due to the brittleness and complete lack of ductility of the material when heat-treated.

It should also be noted from the results that "Unisil" and Dentaurum Remanit "Super Spring Hard", both precipitation-

hardening stainless steels, have higher values for .02 per cent proof stress than does Wilcock "Special Plus".

Also it is noted how close are the values for .02 per cent proof stress for Wilcock "Special Plus" and "Special".

TABLE 6

Values Obtained for Proportional Limit
and .02% Proof Stress

Material	Proportional Limit (1000 lbs/sq. in.)		.02% Proof Stress (1000 lbs/sq.in.)	
	Mean	S.D.	Mean	S.D
Wilcock Special Plus	261	4.8	281	7.2
Wilcock Special	257	4.9	275	8.1
Wilcock Regular Plus	253	8.5	269	8.9
Wilcock Regular	205	7.9	220	9.6
Dentaurum Remanit Super Spring Hard	277	3.4	295	6.6
Unisil	303	3.1	317	6.1
Red Elgiloy (Heat Treated) 482°C	269	3.4	286	4.4

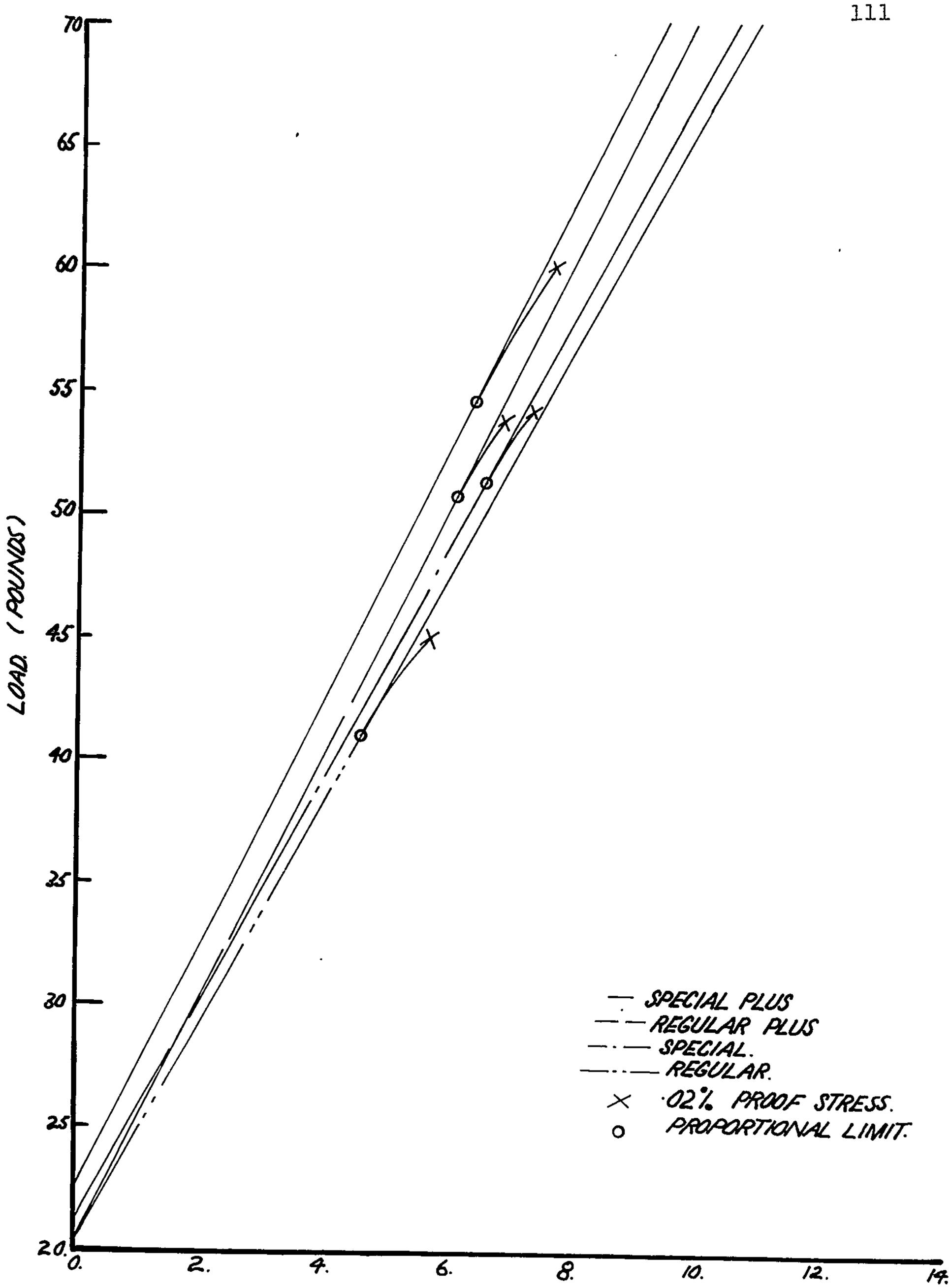


FIG 21.

TYPICAL LOAD-STRAIN CURVES. FOR WILCOCK RANGE OF WIRES.

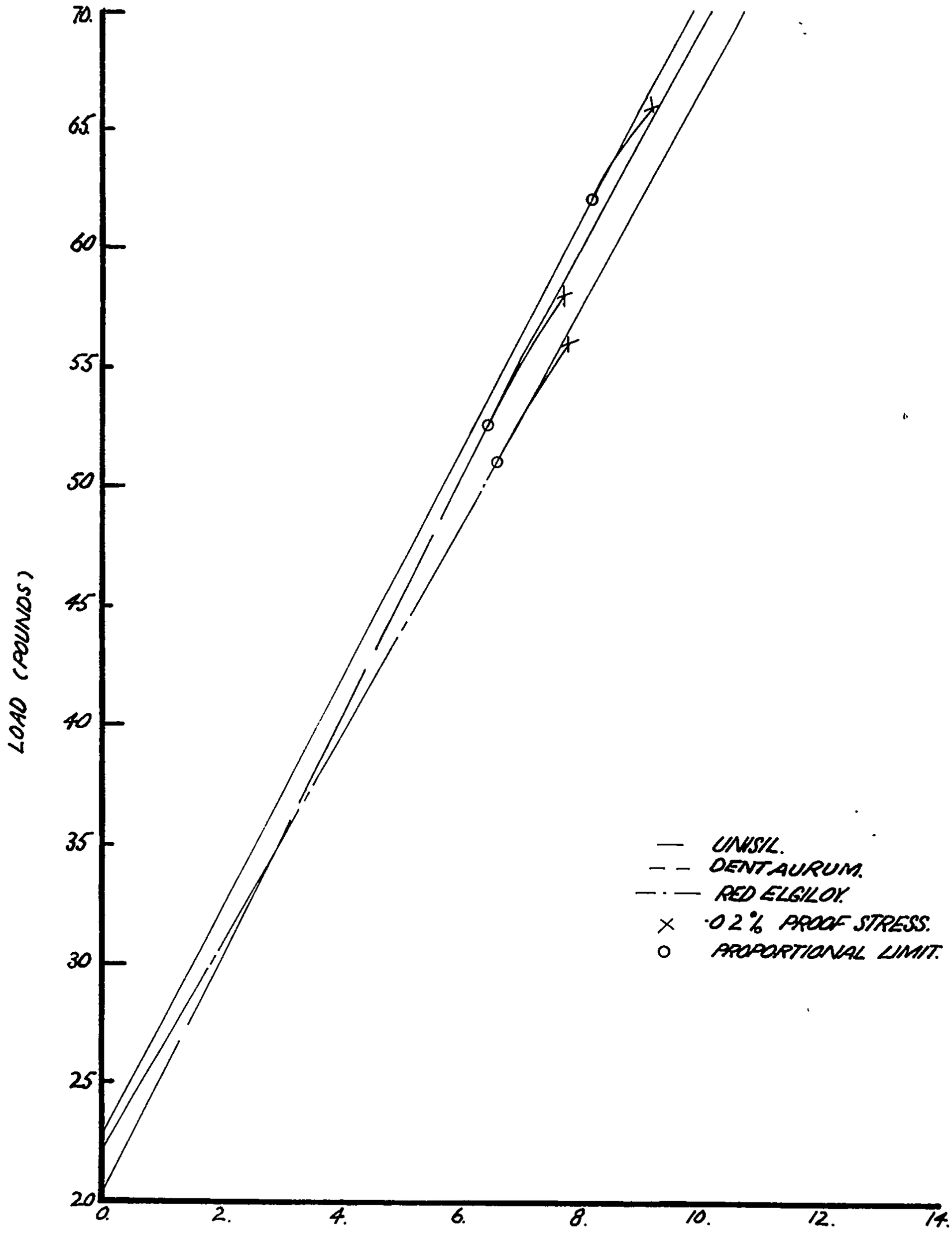


FIG 22.

TYPICAL LOAD STRAIN CURVES FOR UNISIL DENTAURUM REMANIT AND RED ELGILOY.

8.3.3. YOUNG'S MODULUS OF ELASTICITY

Values for moduli of elasticity are given in Table 7. Unisil and Wilcock "Regular" were the wires with the lowest moduli of elasticity. The highest value was that obtained for Dentaurum Remanit "Super Spring Hard", followed by Wilcock "Special Plus. The remaining Wilcock wires, "Special" and "Regular Plus", were in the intermediate range and had similar values. "Red Elgiloy" had a value comparable with the stainless steel wires.

Discussion

The accepted value for modulus of elasticity of stainless steel has always been approximately 30×10^6. This project has shown that we have been mistaken in making this assumption and that the value for modulus of elasticity does vary as regards the wires under test. This variation in values is most likely due to the amount of cold work and stress relief heat-treatment that the wire has undergone during manufacture.

It will be noted that the value for modulus of elasticity increases through the range of Wilcock wires from "Regular" up to "Special Plus". No attempt should be made to predict what effect heat-treated would have on the modulus of elasticity of "Unisil". But it might be noted that Dentaurum Remanit "Super Spring Hard" is a precipitation-hardening stainless steel that has been heat-treated and that its modulus of elasticity was the highest of all the wires tested at 26.1×10^6.

TABLE 7

Values Obtained for Young's Modulus of Elasticity in Tensile

Material	Modulus of Elasticity (lbs/sq. in.)	
	Mean	S.D.
Wilcock Special Plus	24.6×10^6	$.78 \times 10^6$
Wilcock Special	23.2×10^6	$.92 \times 10^6$
Wilcock Regular Plus	23.2×10^6	$.70 \times 10^6$
Wilcock Regular	22.8×10^6	$.88 \times 10^6$
Dentaurum Remanit Super Spring Hard	26.1×10^6	$.76 \times 10^6$
Unisil	22.8×10^6	$.78 \times 10^6$
Red Elgiloy (Heat Treated) 482°C	23.4×10^6	$.45 \times 10^6$

8.4. BEND TESTING

8.4.1. ELASTIC LIMIT

Values obtained for the elastic limit for "Unisil" and Wilcock "Special Plus" are contained in Table 8.

Discussion

The values for elastic limit in bending may seem exceedingly high to the reader when compared with the values for proportional limit or proof stress in tensile. However as explained in Section 5.3.3. the value registered on the load deflection curve is that of the assumed elastic limit, as in bending there is a combination of tensile and compressive strain.

8.4.2. MODULUS OF ELASTICITY IN BENDING

Values for modulus of elasticity in bending are contained in Table 8 also.

Discussion

It will be noted that the value for Young's Modulus of Elasticity in tension for Wilcock "Special Plus" was very similar to the value obtained for modulus of elasticity in bending. On the other hand, value obtained for Young's Modulus for "Unisil" was a good deal lower than that obtained for modulus of elasticity in bending.

There is not a great deal of information available with regard to variations in moduli of elasticity in tension or bending. The author's opinion is that the Wilcock "Special Plus" had similar

values for moduli because it had undergone stress-relief heat-treatment, whereas "Unisil" was in the cold-worked condition and would contain many internal stresses which are unpredictable. (The author was anxious to obtain samples of preformed "Unisil" archwires which had undergone heat-treatment in order to see what effect this heat-treatment had on the modulus of elasticity in bending, but supplies of these archwires were not yet available by the time this thesis was due for completion.)

TABLE 8

Values Obtained for Elastic Limit and
Modulus of Elasticity in Bending

Material	Elastic Limit (1000 lbs/sq.in.)		Modulus of Elasticity (lbs/sq.in.)	
	Mean	S.D.	Mean	S.D.
Wilcock Special Plus	651	8.6	24.3×10^6	1.5×10^6
Unisil	676	8.4	24.8×10^6	1.2×10^6

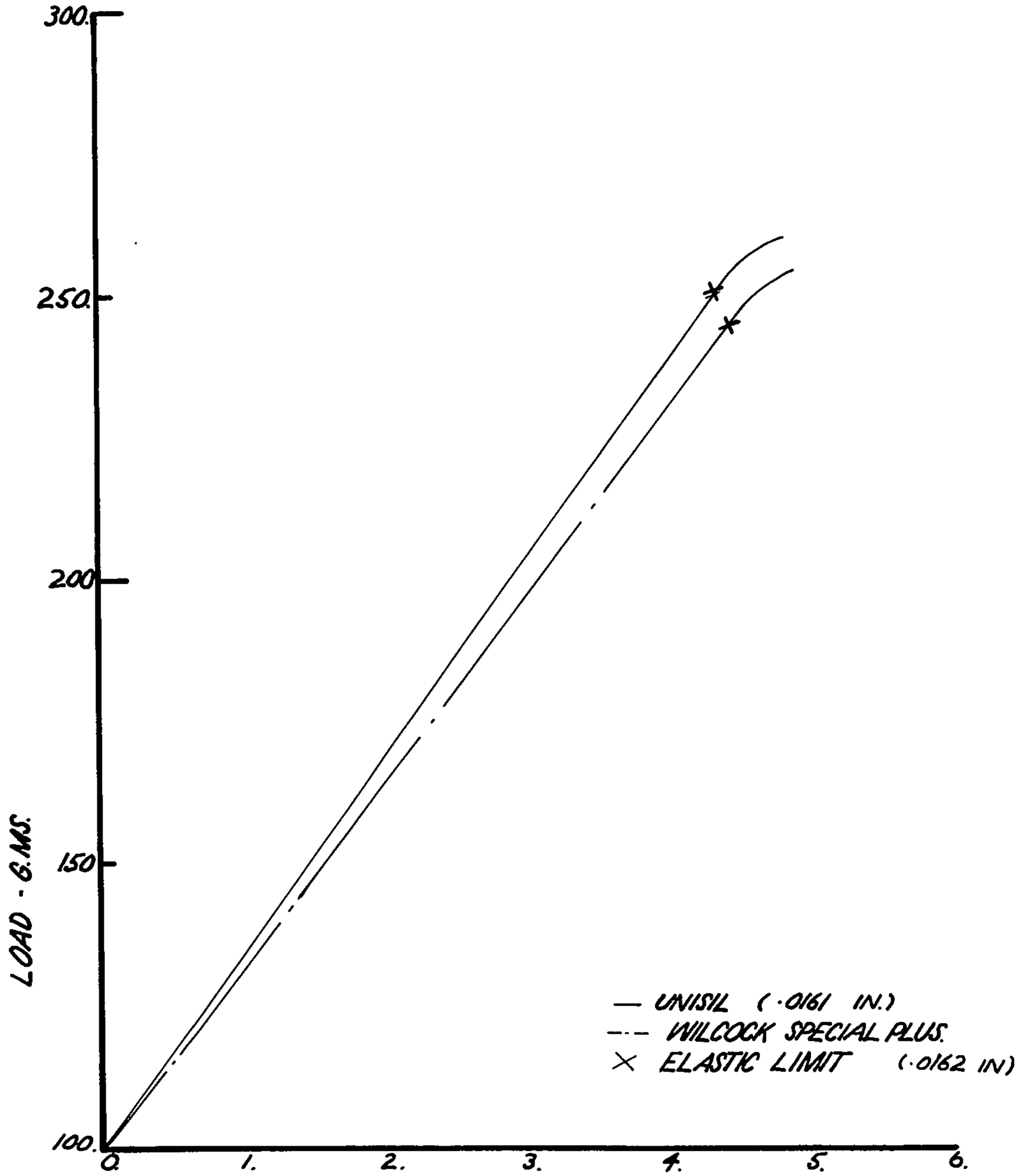


FIG 23

TYPICAL LOAD DEFLECTION CURVES
FOR UNISIL AND WILCOCK SPECIAL PLUS.

8.5 FLEXIBILITY

Values were calculated for flexibility from tensile and bend tests and these were compared and expressed as a ratio in Table 9. From this Table it can be seen that "Unisil" was more flexible than Wilcock "Special Plus".

Discussion

Flexibility (5.3.4.) is distortion due to bending. All orthodontic archwires are subject to bending during use in the mouth. The wire may be bent either by the orthodontist during the course of treatment (e.g. when the wire is attached to a malaligned tooth to move it back into the arch) or during mastication. Especially does the last feature apply to the Australian (Begg) Light Wire Technique. Distortion of the archwire across the span from the canine to the anchor tooth is one of the problems associated with the technique. The more flexible the wire used the less danger there is of this problem arising. The aim of this project was to find which of the wires under test was most suitable for use in this technique.

In determining a value for flexibility one is able to correlate a greater portion of the data with regard to mechanical properties collected during this evaluation, from both tensile and bend testing. Wilkinson[64] and Mutchler[40] wrote of the resilience of the wires tested and applied the formula $\frac{P^2}{2E}$ (P = proportional limit and E = modulus of elasticity) to obtain this value. Wahl[59] also gives this formula for determining resilience, but

as can be noted in Section 5.1.8. this is a value for strain energy in tension and has no connection with the performance of the wire in bending.

In order to obtain a value for flexibility, it is necessary to take into account the modulus of elasticity, the elastic limit and diameter of the wire. Especially is the diameter of importance as it has such a bearing on the performance of the wire in bending (see Section 5.3.2.). Brumfield's formula for flexibility (Equation 9) was therefore applied to values obtained from tensile and bend testing.

The results obtained for flexibility calculated from tensile and bend testing suggest a reasonable correlation, the ratio of flexibility of "Unisil" to Wilcock "Special Plus" from tensile values was 1.22 : 1 and that from values obtained in bending was 1.06 : 1.

These figures show that it is possible to carry out tensile testing when assessing a wire and calculate a value for flexibility, which would have a close similarity to that figure obtained from bend testing. However if the right equipment were available to carry out bend testing, e.g. a Tineaus Olsen bend testing machine, it is the author's view that it would be preferable to carry out bend testing and use the tensometer for obtaining a value for tensile strength only.

TABLE 9

Comparison of Flexibility from Tensile and Bend Testing of Unisil and Wilcock Special Plus

Material	Ratio of Flexibility from Tensile Test	Ratio of Flexibility from Bending Test
Wilcock Special Plus	1.00	1.00
Unisil	1.22	1.06

TABLE 10

Result of Random Testing of Wilcock Special Plus Wire.
Values Obtained for U.T.S. and Subsequent Classification.

Batch Number	U.T.S. (1000 lbs/sq.in.)	Classification
C.RCC	372	Type C
T.ROA.	386	Type C
B.ROL.	410	Type D
O.RCL	386	Type C
D.R.CC.	388	Type C
Re-imported Australian Wire T.P. Lab. 1632	375	Type C
T.P. Lab. 1821	386	Type C

8.6. FINAL DISCUSSION - CLINICAL SIGNIFICANCE OF FINDINGS

The final assessment of "Unisil" and Wilcock "Special Plus" can be covered by relating the findings of this evaluation with their clinical significance. This can best be done by considering:

(a) Flexibility, which combines all the elastic properties of the wires.

(b) The elastic limit in bending and the ultimate tensile strength.

(c) Ductility.

(a) It has already been discussed in Section 8.5. how significant is the flexibility of the wire, in avoiding distortion of the archwire across the span from canine to the anchor tooth. Any distoration of the archwire in this region will negate the effect of the anchor and/or bite opening bend.

(b) The higher the elastic limit in bending combined with a high ultimate tensile strength, the better the anchor and/or bite opening will function and the less chance of it being "bitten out".

(c) It is essential that the wire which has the first two properties also has sufficient ductility to allow incorporation of intermaxillary circle loop or "boot hooks" in the archwire.

The results of this laboratory evaluation have shown that the wire that best satisfies all these requirements was "Unisil".

CHAPTER 9

9. SUMMARY

(1) The significant mechanical properties of six proprietary stainless steel wires and a cobalt nickel alloy wire were evaluated.

(2) The theme of the literature review was that the progressive development of new orthodontic techniques over the years has been dependent on two factors:

(a) The ingenuity of the clinician.

(b) The availability of newer and better archwire material.

Especially was this shown to be true of the Australian (Begg) Light Wire Technique. The method of assessing these wires as they were developed was by comparison of their mechanical properties.

(3) Numerous .016 inch diameter wires are available for use in the Australian (Begg) Light Wire Technique. An assessment of their mechanical properties was indicated.

(4) Tensile, ductility and bend testing were carried out.

(5) From the tests values were obtained for:

(a) Ultimate Tensile Strength (U.T.S.)

(b) Proportional Limit

(c) 0.02 per cent Proof Stress

(d) Young's Modulus of Elasticity

(e) Maximum Ductility

(f) Elastic Limit in Bending

(g) Modulus of Elasticity in Bending

(h) Flexibility (Calculated Value).

(6) A random test to determine the U.T.S. values of seven various samples of the wire of one manufacturer was also undertaken.

(7) From a comparison of the values obtained for the properties of the various wires under test the following conclusions were drawn.

CHAPTER 10

10. CONCLUSION

(1) "Unisil" brand wire was shown to have mechanical properties which would make it most suitable for use in archwire construction for Stage 1 and Stage 2 of the Australian (Begg) Light Wire Technique.

(2) "Unisil" was classified a Type D wire.

(3) Two of the wires in the Wilcock range failed to achieve their previous classification, namely Wilcock "Special Plus" and "Regular".

(4) Wilcock "Special Plus", although it failed to come up to specification, was shown to be the second most suitable wire.

(5) Random testing of seven separate batches of Wilcock "Special Plus" wire confirmed the findings with regard to its failure to come up to specifications for a Type D wire.

(6) Wilcock "Special Plus" was reclassified Type C.

(7) Young's Modulus of Elasticity for stainless steel orthodontic wire in the cold-worked or heat-treated condition is not a constant value, and this must be taken into consideration when evaluating the properties of such wires.

(8) From this evaluation having noted the relationship of proof stress to ultimate tensile strength has varied for different wires, the author would suggest that manufacturers be

requested to supply the value for .02 per cent proof stress in addition to the value for the ultimate tensile strength for their wires, and that this value be included in the Australian Standard T32. Especially is this necessary if the wires are to be used in the Australian (Begg) Light Wire Technique.

(9) In view of the findings with regard to Wilcock "Special Plus" and Wilcock "Regular" the author would recommend that the Bureau of Dental Standards carry out more frequent testing of orthodontic wires currently available. Failing this, and appreciating the load already placed on the Bureau, as it serves all phases of dentistry, the Australian Society of Orthodontists could appoint a committee to investigate and report on orthodontic wires currently available and on new wires as they become available.

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