sciendo DOI: 10.2478/aoj-1989-0005

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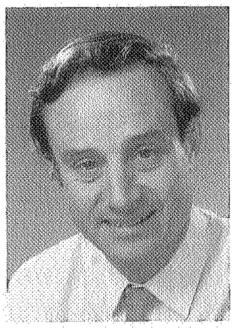

# Applied materials engineering for orthodontic wires

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**Abstract:** In Australia, the history of materials engineering for orthodontic wires is generally related to the development of the Begg appliance. Therefore, until recently, it has helped in the search for *light resilient forces* produced by fine high-tensile stainless steel wires. Recently there has been added the desire to include wires of a low modulus of elasticity which also produce light forces but in larger diameter rectangular wires. There have been three periods of development, namely, up to and including the Second World War, up to Dr Begg's passing, and subsequently.

A general metallurgical background for archwire selection and use is given including the following considerations: stiffness, flexibility, zero stress relaxation, formability, resiliency, high yield phenomena, and wire fracture and crack propagation; and how some of these may be *evaluated by the fingers*.

**Reference:** Aust.Orthod.J.11(1):22-29

**MeSH words:** metallurgy, orthodontic appliances
**Key words:** Begg appliance, wire stiffness, wire flexibility, zero stress relaxation, wire fracture and crack propogation

## INTRODUCTION

It is perhaps timely, now that both Dr Begg and my father Claude Arthur J. Wilcock have passed on, that an historical account be given of their early association in the development of the Begg appliance and its dependence on high tensile stainless steel light wires.

Few people today would appreciate how scarce, expensive and little understood stainless steel was during the early pioneering years of the Begg technique. Indeed, stainless steel was something of a novelty having only become commercially available in the late '1920s'. Its scarcity became even more acute through World War II. This is emphasised by correspondence in our possession, wherein people were asked to return samples not used immediately.

In recent years there has been a trend in orthodontics towards even lighter forces for which Titanium alloys have now replaced stainless steel in *certain* instances. However, it has been a major objective of the following article to illustrate in engineering terms, that by employing ultra high tensile wires, stainless steel still has a major role to play in orthodontic wires.

## HISTORICAL BACKGROUND

In 1929 Claude Arthur J. Wilcock applied for the position as a cadet engineer at the metallurgy workshops, University of Melbourne, under the late Professor J.N. Greenwood. This position enabled him to study part-time at the Production Engineering School, Melbourne Technical College (now the Royal Melbourne Institute of Technology) and at the same time gain a unique experience with the professor and undergraduates in the development of metallurgical test and research equipment during work hours.

His outstanding mechanical and technical aptitude, first evident in his school reports as a student at the Junior Melbourne Technical School, did not go unnoticed by Professor Greenwood who eventually put him in charge of the metallurgy workshop before the age of twenty five years.

His association with the dental profession began in 1936-37 with the forming of the Bureau of Dental Standards (now the Australian Dental Standards Laboratory). This was comprised of people from the Melbourne Dental Hospital, Professor Greenwood and others from the metallurgy school. This involved him in the design and manufacture of much of the test, quality control and research equipment for the laboratory.

With the entry of Japan into World War II, American supplies of orthodontic appliances and materials to Australia became doubtful and as a consequence, a group of eminent dentists and metallurgists formed a committee to consider manufacture in Australia. That committee also included my father.

It was during this period that a special war time project known as the 'Tungsten Project' carried out the development of a pilot plant at the metallurgy school, Melbourne University, to produce fine tungsten filament wire. The special equipment for hot swaging, rolling and wire drawing, had to be made in the workshops by my father, and so his special knowledge in wire drawing began.

It should always be kept in mind however, that the orthodontic wires were only a spin-off from the metallurgical research equipment that was being developed at the time. Little was it realised what it would lead to – with the first few samples supplied to Dr Begg.

The first actual meeting with Dr Begg is unclear. Nothing was documented on this subject although correspondence certainly began early in 1946, so their acquaintance probably goes back to the war years at the University of Melbourne.

Early in 1946, my father left the University to set up his own business and as far as I know produced most of Dr Begg's materials. This included flux, silver solder, bands, brackets, lock pins, ligature wire, pliers and most importantly, the high tensile orthodontic wire.

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These appliances for Dr Begg were hand made and crude by today's standards, however they were sufficient for the master to develop his technique. Dr Begg's main problem, and he made this patently clear in personal correspondence with my father, was the real need for a wire that remained active in the mouth for long periods. Many of his patients came from hundreds of miles away, so frequent appointments were out of the question and this was probably the motivating factor in Dr Begg developing a revolutionary technique, requiring less adjustments and hence fewer visits. Necessity is surely the mother of invention and so the light differential force tooth movement technique was born but it needed two very dedicated men.

My earliest recollection of this work goes back to the '1950s' as a boy. I remember the first wire drawing machine, a real Heathrobinson of a gadget, consisting of an old truck differential mounted on a waterpipe frame. Everything was secondhand – usually parts from old cars and trucks if they could be adapted. But it did the job. Some of the original machine parts are still in existence today.

It is all very well to have two inventive minds but, as with the promotion of any new product, it needs an entrepreneur and so entered the late Dr H.D. Kesling of the USA upon the scene in 1957 to promote and further develop the Begg Light Wire Technique worldwide.

The new association with Dr H.D. Kesling meant many of the old ways for supplying Dr Begg with material had to be abandoned. My father and Dr Begg in their association had become like two old cronies. What worked in Dr Begg's hands did not necessarily work for others, as over the years Dr Begg had kept asking for progressively harder and harder wire to the point where a raw beginner would probably have difficulty handling such high tensile wire.

Hence it was necessary to grade the wires produced by A.J.Wilcock Scientific and Engineering, which was at the time located in Melbourne, to allow users to choose which grade they could cope with, into:
1. Regular (at the low end)
2. Regular Plus
3. Special (the middle of the range)
4. Special Plus (at the high end)

Around 1960, the production of brackets silver-soldered to bands, pliers, lock pins etc., were slowly phased out, or rather we could not meet the increased demand as the production methods were far too slow and inefficient to compete with the American counterparts.

This did not seem to concern my father as his real interest lay, even right up until his death, in metallurgical research equipment, where he had an established name for quality. It was this dedication to the field of metallurgy that attracted the attention of the Australian Metallurgical Society and eventuated in him being awarded the 1982 Florence Taylor medal for outstanding services in the field of metallurgy. It was the first time in the long history of the annual award that it was given to a person without formal qualifications in metallurgy.

Prior to my own involvement with the orthodontic wire production which began after my student days in engineering in the late '1960s', all raw material wire supplies had been obtained from local warehouse stockists. This had never been satisfactory and was very much a haphazard arrangement. We could not always purchase the ideal material and even if we could, never in the right quantities and delivery was slow.

By the early '1970s' the demand worldwide for our wires had become so great that it was imperative to seek raw materials with the correct analysis in sufficient quantities directly from the manufacturers overseas. This in turn helped to develop even higher grades (Premium) because the ordering became more precise and enabled us to produce consistently higher tensile wire in sufficient quantities.

In the early '1970s' preformed archwire appliances, torquing auxiliaries, springs etc. were becoming mass produced to reduce orthodontists' chair time of hand fabrication of appliances.

However, there were several serious problems with preformed appliances formed from the high tensile wires we were manufacturing.

(a) The impossibility with existing methods to straighten our highest tensile wires for subsequent forming into appliances.

(b) Work softening occurring in the wires that were being straightened.

(c) The conventional wire forming concepts were not appropriate to our unique wire. So the highest tensile wires kept breaking during forming. In most cases this was not because of the wire quality but through lack of lateral thinking in developing suitable forming fixtures.

I recently had the opportunity to inspect a company which manufactured preformed appliances for several orthodontic suppliers. In all instances the tooling techniques were applicable to commercial stainless steel wires. Spring making companies prefer to use a softer, less resilient grade of stainless steel wire compared to our own. These other grades exhibit better forming characteristics because of their higher elongation and hold closer tolerances during fabrication, with a complete absence of brittleness. Medium grade wires of our own manufacture do lend themselves to easier forming as they have been subjected to less work hardening and hence are more ductile. However, our feedback is that it is the hardest wire, that is, Premium grades, which exhibit the least relaxation which are preferred for use as an orthodontic archwire.

Herein lies the problem: how to produce preformed appliances with the best wires, since no commercial company is prepared to work with the highest grades. They will, however, work with the lower and medium grades but the existing methods for straightening the wire was spoiling the very property we were trying to develop in the wire. This problem was subsequently overcome, although not until the early 1980's but that will be discussed later.

## APPLIED MATERIALS ENGINEERING

### *WIRE SELECTION*

A decision needs to be made whether the appliance is active or passive in function.

Most properties can be assessed simply by the feel the wire has in the hands:

(a) Flexing the wire in the fingers without taking a set is a quick measure of its flexibility

(b) Forming an arch with the thumb gives some indication of the force needed to deform the material, that is, its stiffness

(c) Measuring how much spring is in the arch by deflecting between the thumb and index finger is a measure of resiliency.

Most of these properties can be defined mathematically from basic engineering concepts, thus permitting an analytical approach in the design of an orthodontic wire.

STIFFNESS can be defined as the ratio of force to deflection of a member.

$$\text{Stiffness} \propto \frac{\text{Load}}{\text{Deflection}}$$

If we consider the segments of the main archwire between each bracket, where the wire has been pinned, we have a similarity between a beam freely supported at both

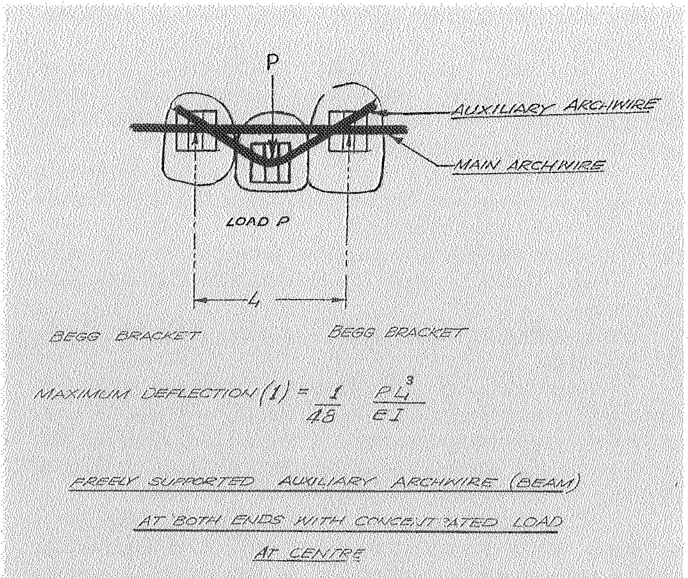



Figure 1. A Begg bracket

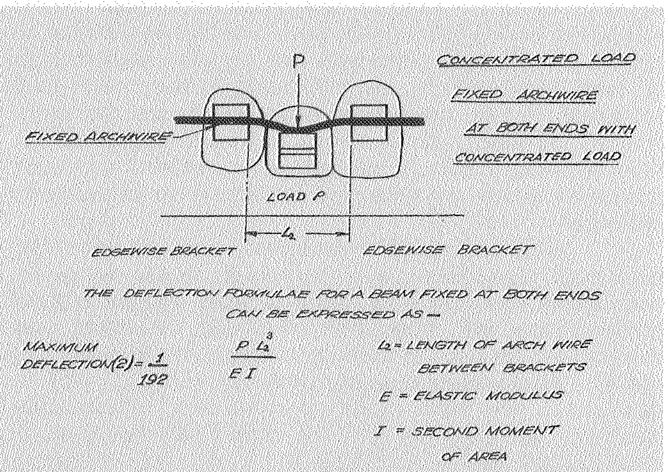
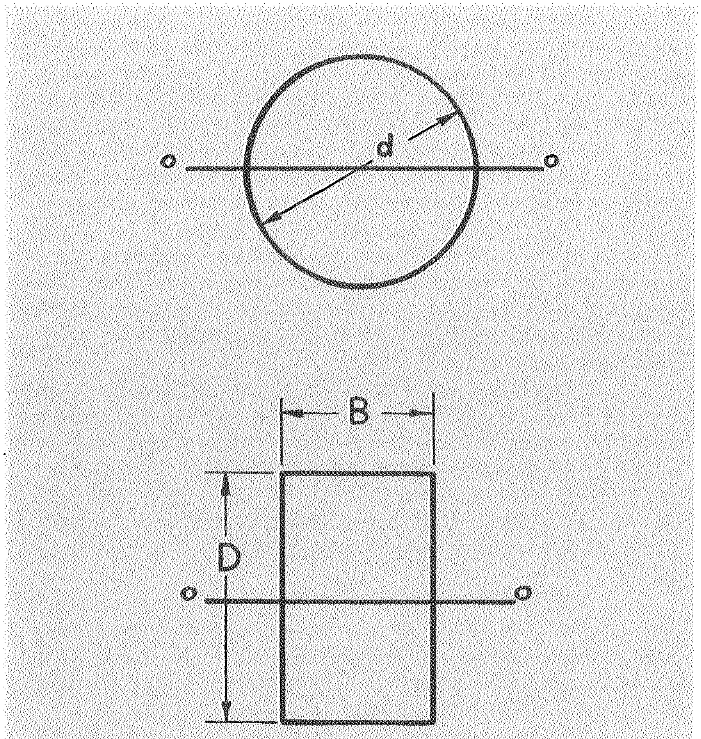



Figure 2. An edgewise bracket. Note that $L_1 > L_2$.




Where $I_{oo} = \frac{\pi . d^4}{64}$ (for round wires)

and $I_{oo} = \frac{BD^3}{12}$ (for rectangular wires)

Figure 3. Second moment of area for round and rectangular wires

ends and loaded at the centre, (Begg bracket) or beam fixed at both ends and loaded at the centre (edgewise bracket).

The deflection formulae for a beam fixed at both ends can be expressed as :

$\frac{\text{Load P}}{\text{Deflection}} \propto$ E.I (Stiffness) [only two variables]

Transposing, Deflection $\propto \frac{P}{EI}$

This means that the stiffness of an archwire can be varied in three ways.

1. The first and traditional approach has been to vary the second moment of area 'I' about the axis of bending.

Thus small changes in dimensions d and D can result in large variations in stiffness.

The difference between ·016" and ·014" diameter is approximately 40%.

2. The second approach is to vary the elastic modulus E. That is, use various archwire materials such as Nitinol which has E = 10 x $10^6$psi, Beta-Titanium 15 x $10^6$psi, Gold alloys 20 x $10^6$psi and Stainless steel 28 x $10^6$psi giving a variation of approximately 3 to 1 with stiffness.

3. A third approach, which is really an extension of the second, is to build up a strand of stainless steel wire, for example, a core wire of ·0065" and six ·0055" wrap wires will produce an overall diameter approximately ·0165 inches. The second moment of area of the strand and an equivalent solid wire would be essentially the same. Young's Modulus is the same for both stainless steel wires yet there is a considerable difference in their respective stiffnesses.

The reason why the strand has a more flexible feel is due to the contact slip between adjacent wrap wires and the core wire of the strand. In general the strand stiffness can be related to the normal forces acting between the wrap wires and this in turn is related to the helix of the strand lay, that is the tightness of the strand lay, giving the impression of a pseudo variable modulus material.

When the stand is deflected the wrap wires which are both under tension and torsion will slip with respect to the core wire and each other. Providing there is only elastic deformation each wire should return to its original position, hence the need for a very high yield point strand material. Unfortunately because of the existing methods of stranding there is an inevitable loss in yield strength during the stranding process due to Bauschinger effects. This loss in yield strength can hopefully be minimised by developing a unique strain age stranding process which we are currently developing with the Supreme grade wire.

**FLEXIBILITY** is a measure of the amount which a wire can be strained without undergoing plastic deformation. This property can be best described by a simple tensile test stress strain diagram (Timoshenko 1955).

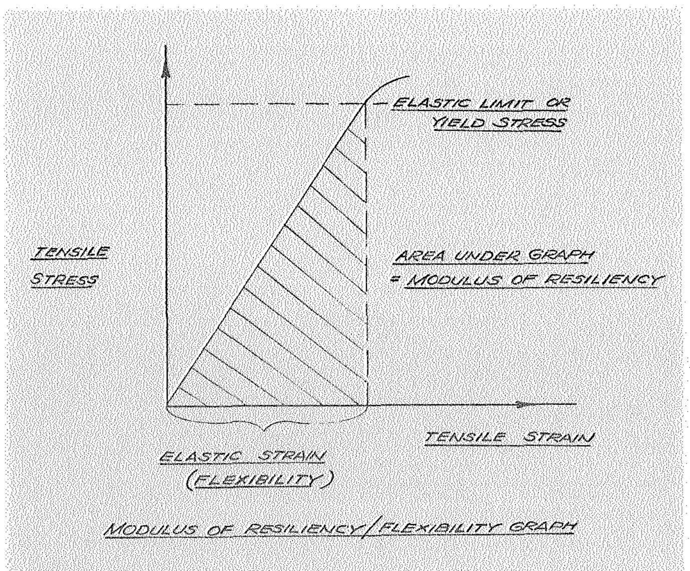



Figure 4. Modulus of elasticity/resiliency

Elastic Strain (Flexibility) $\propto$ Tensile Strain

$$\text{Elastic Modulus} = \frac{\text{Yield stress}}{\text{Elastic strain}} \quad \text{(Hooke's Law)}$$

(Hazel and West 1986)

$$\text{Flexibility} = \frac{\text{Yield stress}}{\text{elastic modulus}}$$

This means a wire with good flexibility needs to have a high yield stress or low elastic modulus.

Resiliency, or more precisely the modulus of resiliency, of a wire is defined as the amount of strain energy per unit volume which can be stored without permanent set.

$$\text{Elastic Modulus} = \frac{\text{Stress}}{\text{Strain}}$$

Thus,

$$\text{Strain} = \frac{\text{Stress}}{\text{Elastic Modulus}}$$

Work done (strain energy) = area under graph

$$= \tfrac{1}{2} \times (\text{elastic stress}) \times (\text{elastic strain})$$

$$\text{i.e. Modulus of resiliency (per unit volume)} \propto \frac{\text{Yield Stress}^2}{\text{Elastic Modulus}}$$

Hence wires with high resiliency should have a high yield stress or yield point of low elastic modulus. Note in this instance it varies at the second power of the yield stress.

## ZERO STRESS RELAXATION

This is the ability of a wire to deliver a constant light elastic force when subjected to an external force or forces of occlusion.

This property is difficult to define in engineering terms. However, it has been determined and verified in written articles that the only wires which possess this most desirable property are dependent on the material yield stress being as high as possible. Relaxation in a material implies that a form of slip by dislocation movement is occurring and this can be related to the internal frictional force, to overcome the movement of dislocations.

In quantitative terms this is probably in the region of 'special plus' and above. This indicates that the wire should have a very high and sharp yield point with low elongation and this depends on the thermomechanical production history during manufacture.

## FORMABILITY

Formability is the ease with which a material can be plastically deformed. This can be related to the percentage elongation a wire can undergo before fracture. Elongation is defined as the percentage change in length at fracture to the original length. Unfortunately wires with high and sharp yield points possess low elongation values.

Hence there is a need for stringent quality control, that is, wrapping test, bend test, forming tests etc., with the highest tensile wires.

## BIOCOMPATIBILITY

Stainless steel has good corrosion resistance in the body. Only in rare instances are we requested to supply titanium for nickel allergy patients.

## TWO PHILOSOPHY APPROACH TO FLEXIBILITY-RESILIENCY

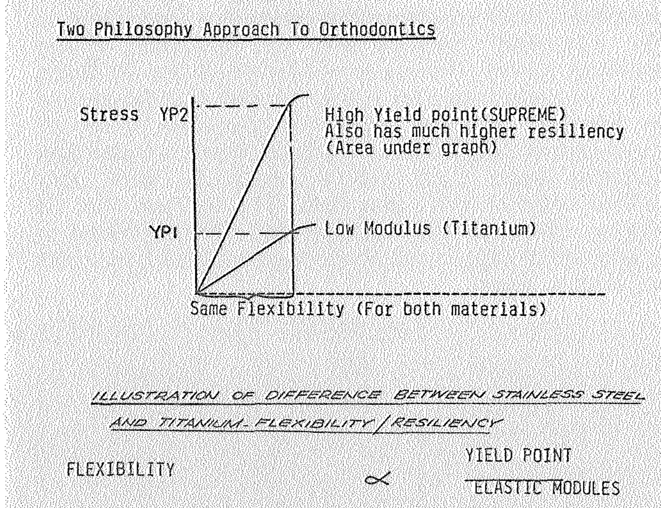



Figure 5. Illustration of difference between stainless steel and titanium flexibility/resiliency

$$\text{RESILIENCY} \propto \frac{(\text{Yield Stress})^2}{\text{Elastic modulus}}$$

$$\text{FLEXIBILITY} \propto \frac{YS}{E}$$

Both properties can be varied by changes in yield stress, that is, grades Regular – Premium Plus, or by a second approach of changing the elastic modulus of the archwire material. This second approach has received considerable attention in the past decade using Titanium wires because of their high flexibility. However, similar flexibility can be achieved by the use of small diameter 18/8 stainless steel wires with ultra high yield points. This approach was initially investigated clinically by Dr B. Mollenhauer in the early 1980's and has attracted so much interest to the point that we are now producing considerable quantities of ultra high tensile wires in ·008, ·009, ·010, and ·011 inch diameter (known as 'Supreme' grade.) These wires were used initially for alignment in lingual orthodontics where the brackets are close together, but were then found to optimise alignment in the labial brackets by reducing tenderness of the teeth and making tooth movement faster. The first wire was ·010" diameter. With the next trial wire, ·009" diameter, observations indicated two bonuses: that gentle alignment could be achieved concomitantly with intrusion, and that gingival health seemed better (Mollenhauer 1987). It has been shown by Hazel and West (1986) that Supreme grade wires have similar flexibility values to Beta Titanium are approximately three times as resilient. Only Nitinol has a superior property in terms of flexibility in comparison to the Supreme grade wire, but at the expense of good formability and at a purchase price many times that of stainless steel.

The commercial production of titanium metal started after the Second World War specifically for the aeronautical industry where titanium alloys of high strength - low weight were sought. These alloys eventually found application in the medical and later orthodontic fields which made possible a variable stiffness approach without changing the wire cross-section by using metals with different elastic modulii.

Although Professor Burstone is credited with this approach in orthodontics, it is of interest to note, and well documented too (!) that Dr Begg and Professor Greenwood were experimenting along the same lines in 1954. The ·018" titanium wire was produced at the metallurgy school, University of Melbourne for Dr Begg, but his comment was that it was too soft and the project was dropped. Titanium alloys are available in several phases (see ternary diagram – (*Figure 6* and see also first reference) alpha close packed hexagonal, beta body centered cubic or alpha plus beta. The titanium that Dr Begg experimented with was probably alpha stabilised by the addition of oxygen and would have suffered from room temperature creep.

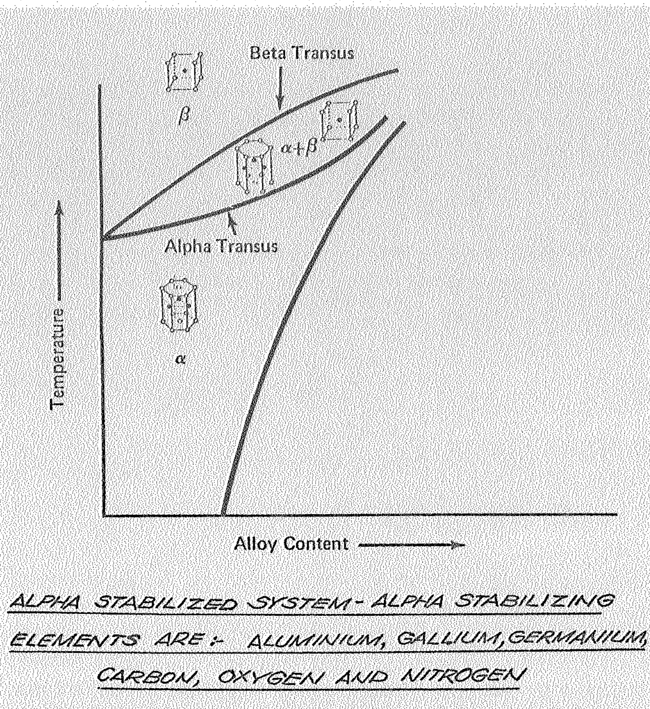



Figure 6. Alpha titanium phase diagram

That is, it would not have possessed a high and sharp yield point. Clinical feed back from the use of beta titanium in orthodontics suggests that it also suffers from mouth temperature creep.

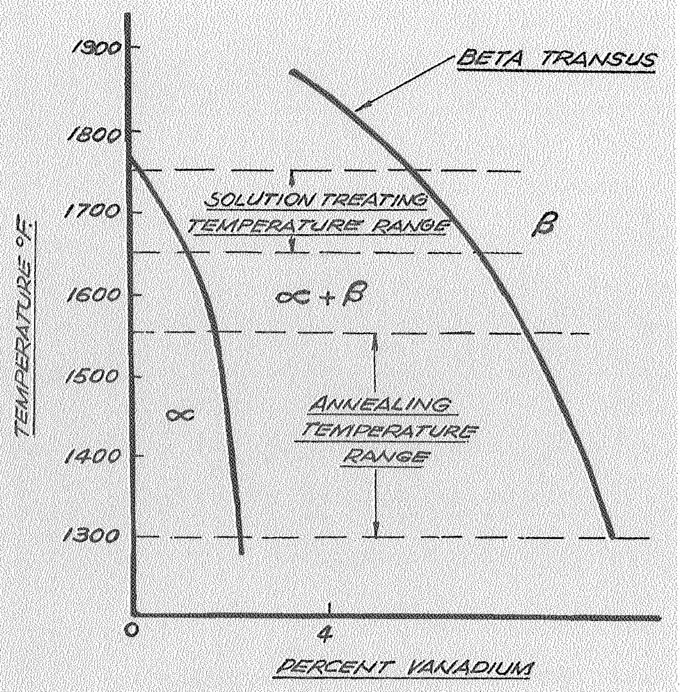



Figure 7. Alpha/beta phase diagram

Most titanium alloys have been researched in terms of elevated temperature creep because of their application as turbine blades in jet engines and the best alloys have shown to be the alpha/beta and more particularly the near-alpha phase alloys. Hopefully this may be indicative of their lack of mouth temperature creep which may prove to be the most useful in orthodontics.

There are several near-alpha alloys worth investigating. Currently we are developing a 6% aluminium 4% vanadium titanium orthodontic wire (ternary diagram – *Figure 7*). This material has been clinically tested in ribbon arch form by Mollenhauer (1988) and found to have satisfactory creep properties as finishing and braking arches for the Begg appliance. One curious aspect he noted about titanium alloys with high aluminium content is that the wire will harden in an oral environment but, after further reading, this is now thought to be due to hydrogen absorption (Polmear 1981). The clinical observations that this alloy becomes stiffer and brittle as the material ages in the mouth needs further investigation to confirm this phenomenon, possibly sue to the formation of titanium hydride.

## THE THEORY FOR HIGH YIELD PHENOMENA

It is quite evident from the property definitions of an orthodontic wire that it is important to produce stainless steel wires with a very high and sharp yield stress or point.

Theory suggests the following means are available for strengthening these wires:

1. work hardening
2. disclocation locking
3. solid solution strengthening
4. grain refinement and orientation.

Most grades of stainless steel are suitable for strengthening by work hardening. By careful selection and work hardening, it is possible to produce yield points well in excess of 200 tons per square inch and still provide wires which possess good formability.

The following graphs will illustrate this point by emphasising the difference in the shape of the stress strain relationship with progressively higher tensile strength wire.

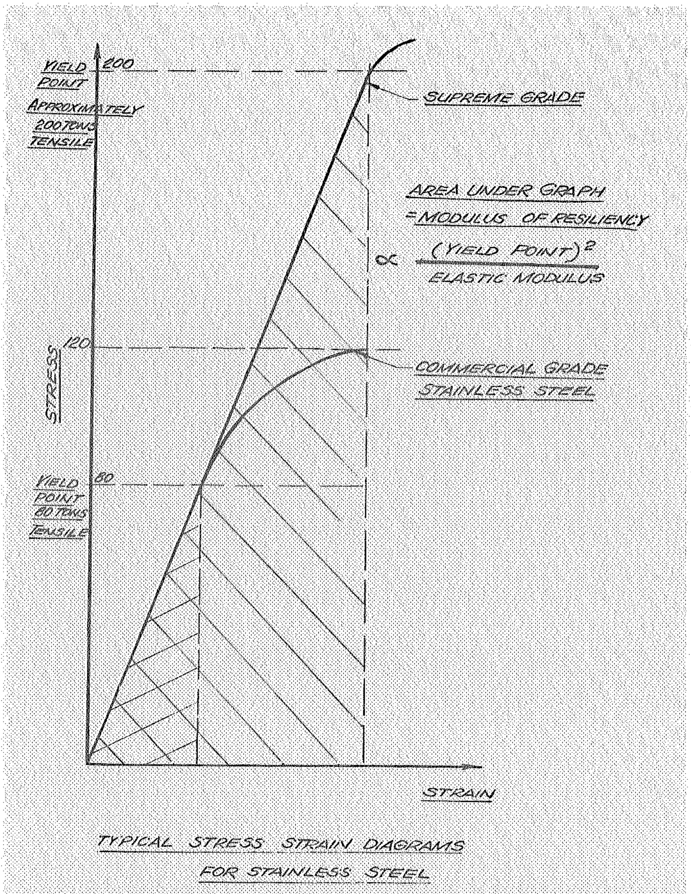



Figure 8. Schematic representation of difference between high tensile and commercial grades of stainless steel wires

High and sharp yield points are related to the freeing of dislocations in a metal crystal and the effective shear stress to move these dislocations (Honeycombe 1984). That is, the flow stress is both dependent on :
1. temperature, and
2. the density of dislocations in the material.

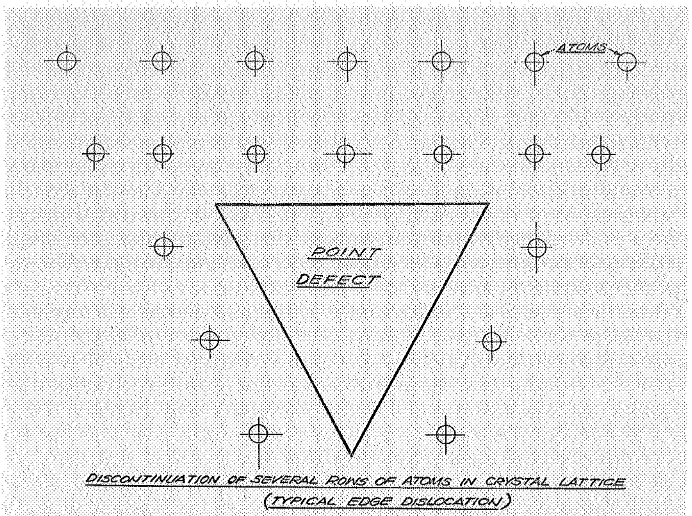



Figure 9. Edge dislocation with point defect

The resulting structure is very hard producing a high flow stress which may involve the creation of point defects at the dislocations such as a vacant lattice site which will be discussed later under the subject of fracture.

Plastic deformation in the absence of dislocation locking will not achieve as high a yield point. Furthermore, if the material is subjected to reverse straining it will possess an even lower yield point in the reverse direction.

This phenomena is referred to as the Bauschinger Effect after it was discovered by Dr Bauschinger in 1886 (Mugharabi 1987).

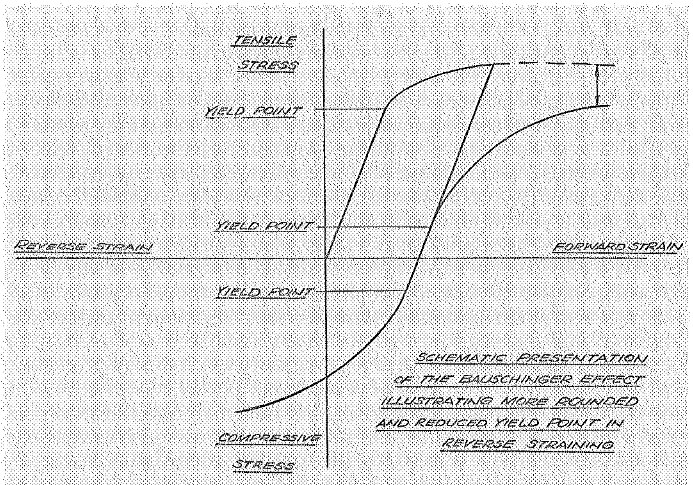



Figure 10. Bauschinger effect

Two important points worth mentioning about this effect are:
1. Plastic prestrain increases the elastic limit of deformation in the same direction as the prestrain.
2. Plastic prestrain decreases the elastic limit of deformation in the direction reverse to prestrain. If the magnitude of prestrain is increased, the elastic limit in the reverse direction can reduce to zero.

Plastic deformation also occurs in metals if strained beyond the elastic limit in compression, tension, torsion (Brown and Watson 1982) and bending. If subsequently subjected to reverse straining the metal will possess a lower yield point than the unstrained metal.

The degree of work softening and loss in yield is determined by the magnitude of plastic deformation and its effect has important implications for orthodontic wires since any loss in resiliency and flexibility would be undesirable. That is why the importance of correct appliance manufacture was mentioned earlier.

All orthodontic appliances have to be subjected to plastic deformation during manufacture particularly with the processes of straightening, stranding, braiding and bending. Wire straightening is a necessary prerequisite for subsequent appliance manufacture such as spring making. The wire is pulled through a series of rollers or spinners subjecting the wire to severe cold plastic deformation and hence work softening. All springs produced by A.J. Wilcock Scientific & Engineering are fabricated from the highest tensile wire and straightened by a special pulsing process (Wilcock 1988).

This process has several advantages over other straightening methods :
1. It permits the highest tensile wire to be straightened, previously not possible.
2. The material tensile yield stress is not suppressed in any way.
3. The wire has a much smoother appearance and hence less bracket friction.

The significance of this in the production of orthodontic springs, assuming the wire activation is in pure bending only, are :
Greater flexibility since :
Flexibility = yield stress ÷ elastic modulus,

Greater resiliency since :
Modulus of resiliency = yield stress over elastic modulus per unit volume.

But more importantly it permits the use of a smaller diameter wire to be used resulting in a lighter and more constant force with minimal or no relaxation, that is, approaching the Begg ideal since :

$$\text{Wire diameter (d)} \propto \sqrt[3]{\frac{\text{Bending moment}}{\text{Yield stress}}}$$

This is assuming the number of coils is small and coil diameter (D) in relation to the wire diameter (d) is as large as physically practicable. *In general*, D - d $\geq$ 4 (Shigley 1986), that is, the coil diameter should usually be four or more times the diameter of the wire.

This has the effect of minimising the reduction in the maximum allowable wire working stress probably at the point of maximum deformation in the spring which is subject to reverse straining, that is, the 'leg to coil' bend.

## WIRE FRACTURE AND CRACK PROPAGATION THEORY IN RELATION TO APPLIANCE FORMING

It might seem at first that this would be a taboo subject for an orthodontic wire manufacturer to broach. However, by addressing this annoying problem and endeavouring to understand the metallurgical phenomena one can thereby minimise its occurrence.

As stated earlier it can be shown that metals with a high density of dislocations, that is, metals with high and sharp yield points such as the Wilcock Special Plus wires and above, have a relationship between the applied stress and the internal stress at the head of dislocation pile-ups. Expressed in simplistic terms this is:

Internal Stress = Applied Stress x Density of dislocations (Honeycombe 1984)

Furthermore, as previously stated, there may be a point defect or defects present at the head of a dislocation where it coalesces with another pile-up. It may form a minute crack and this is usually where a fracture occurs. One hypothesis is that the stress concentration at the head of a crack or point defect is so high that only a small applied stress with the plier beaks is necessary to initiate transgranular crack propagation. The crack is associated with the release of elastic energy and accelerates to the nearest grain boundary. If there are carbide precipitations along the highly elongated grain boundaries only a small amount of surface energy is needed to split the grains. Hence, if the surface energy is less than the elastic energy released by the moving crack, the crack will continue until the crack head is blunted by it own plastic deformation and stops. This is why a crack can sometimes travel up to half an inch from the point of bending, giving the appearance of the wire skin splitting from the main wire.

There are several means of avoiding or minimising the annoying occurrence of wire fracture during bending.

1. Bending the wire around the flat beak of the Begg light wire pliers. This has the effect of introducing a moment about the thumb and wire gripping point thus reducing the applied stress that might otherwise cause wire fracture.
2. The flat beak should have rounded edges to reduce the stress concentration at the bend in the wire.
3. The wire has a ductile brittle transition temperature which may be around room temperature or slightly above, this is why we have always recommended warming the wire by pulling through the fingers first before bending. A more convenient way is to place the wire plastic spool in a warming cabinet at approximately 40°C or oral temperatures, the specific heat of the plastic being much higher than the metal will ensure the wire maintains its temperature when removed from the oven giving sufficient time for bending into archwires.

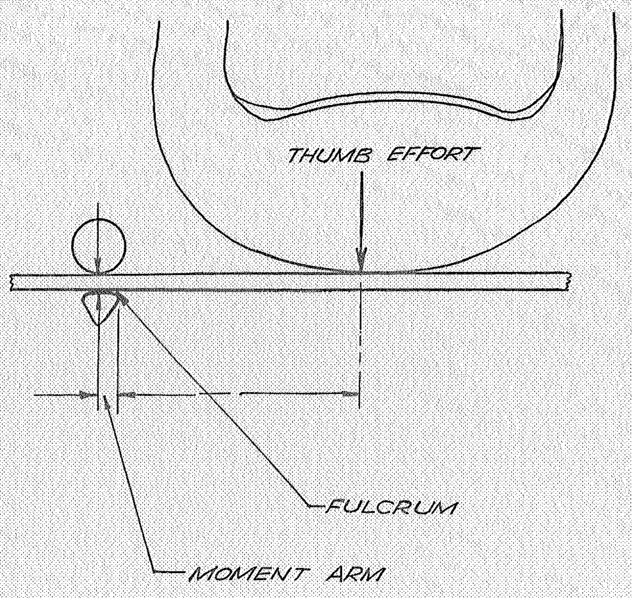



Figure 11. Bending plier around flat plier beak

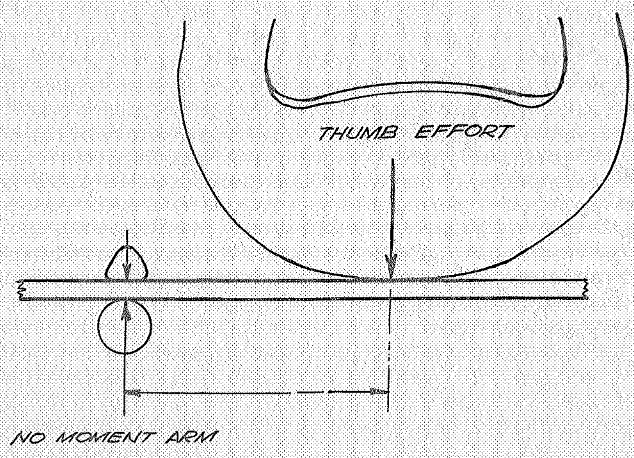



Figure 12. Bending wire around round plier beak

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