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The Bauschinger effect in stainless steel orthodontic wires

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Abstract: The existence and clinical importance of the Bauschinger effect has received little attention in the orthodontic literature. Essentially, the Bauschinger effect describes the reduction in yield stress of a metal when the direction of deformation is reversed. A method of evaluating this phenomenon in orthodontic wires is described and its clinical implications are discussed.

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Key words: Bauschinger effect, reverse bending, orthodontic wires

INTRODUCTION

There are three main methods for assessing the mechanical properties of an orthodontic wire, namely:
(1) Tensile testing
(2) Cantilever beam testing, and
(3) Wrapping tests.

The last two methods have the advantage of evaluating the behaviour of a wire in bending, the mode of deformation usually encountered in the clinical situation.

The aim of this investigation was to evaluate the effect of a change in the direction of loading on the properties of orthodontic wires. It was achieved by subjecting wires to bending stresses utilising the method used in one of the wrapping tests, namely the mandrel test devised by Waters (1972), then testing the same wires in tension. The level of pre-strain was varied by wrapping wire samples around mandrels of various diameters and subsequently the tensile data was compared. Any change in mechanical properties associated with a change in loading direction may be related to the Bauschinger effect.

The Bauschinger effect was first reported in the metallurgical literature by J. Bauschinger in 1886 but did not become the subject of more intensive investigation until the 1950s. Little mention has been made of the existence and clinical significance of this phenomenon in the orthodontic literature (Ingerslev,1966; Burstone, 1985).

In general terms, the Bauschinger effect describes the phenomenon whereby the resistance to further plastic deformation of a wire is *greater if the load is applied in the same direction as the original load* than it is if the direction is reversed. That is, the load that can be resisted by a previously plastically deformed metal object before undergoing further permanent deformation is greater, if applied in the same direction as the force responsible for the original plastic deformation, than if applied in the opposite direction (Ingerslev,1966). In other words, the Bauschinger effect is manifested by the lowering of the yield strength whenever the direction of the applied force is opposite to that of the original deforming force.

Polakowski (1966) suggested that the Bauschinger effect is one feature of plastic flow that results from the anisotropy of the individual crystal grains and specifically, from the variation of elastic modulus and yield strength with orientation of the grains.

Dislocation movement is believed to be the underlying mechanism of the Bauschinger effect. Orowan (1959) has suggested that during plastic deformation dislocations pile up and accumulate in tangles at various microstructural obstacles, and eventually form cells. When the load is removed, the dislocation lines will not move appreciably because the structure is mechanically stable. However, when the direction of loading is reversed, some dislocation lines can move an appreciable distance at a low shear stress because the barriers to the rear of the dislocations are not likely to be so strong and closely spaced as those immediately in front. This gives rise to initial yielding at a lower stress level when the loading direction is reversed. This occurs not only when compression follows extension and vice versa but also when torsion is followed by a reversed twist; or bending followed by bending in the opposite direction.

Polakowski (1966) suggested that since the level of internal stresses increases with prestrain, the Bauschinger effect must increase accordingly.

Dieter (1976) noted that the Bauschinger effect can have important consequences in metal-forming applications. It could result in work-softening when severely cold-worked metals are subjected to stresses of reverse sign. Work-softening of a material would reduce the yield strength and increase the elongation from its cold-worked value.

Burstone (1985) suggested that the Bauschinger effect was responsible for the difference in the range of activation of orthodontic coil springs when loaded in different directions. Activation of a coil in the same direction as it was originally wound gave the greater range of activation ("correct method of loading"). Activation in the opposite direction resulted in a smaller working range ("incorrect method of loading"). Burstone added that in many archwire configurations, in which residual stresses are high, such as in a vertical loop employing a number of coils at the apex, *the range of activation can vary as much as 100 per cent or more between correct and incorrect loading.*

A whole issue of Materials Forum (vol10 no1) is devoted to the Bauschinger effect.

MATERIALS AND METHODS

Wires tested

0.40mm (0.016″) round Wilcock† stainless steel wires, supplied in spool form, were used in this investigation. Various grades of Wilcock stainless steel wires are

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available and are classified according to tensile strength. All grades of these wires gave the same composition and it would appear that the different properties are produced by varying the thermo-mechanical treatments during manufacture. The grades tested here included Regular, Special Plus and Premium Plus.

Wrapping apparatus

The mandrels were machined from mild steel and were finished with a smooth, highly polished surface. Each mandrel was at least 100mm in length and the diameters included 38mm, 25mm, 15mm, 10mm, 6.3mm and 3.23mm.

For each test, the selected mandrel was mounted in the chuck of a lathe with its long axis horizontal. In the larger mandrels (10mm diameter or greater) a 1mm diameter hole had been drilled across the diameter of the mandrel. The test wire could be inserted into this hole and then locked into this position by means of a flat-ended screw placed into a threaded hole tapped down the long axis of the mandrel to meet the radial hole at its base.(*Figure 1.*)

The test wire was located so that any initial curvature of the wire was aligned parallel to the plane of the cross section of the mandrel. After being fixed in the hole, the wire was then bent at right angles to itself so that it would leave the radial fixing hole at a tangent and in the same plane as the initial curvature of the wire. For tests on the 6.3mm and 3.23mm mandrels the test wires were fixed by engaging one end of the wire between the jaws of the chuck and the mandrel.

A small loop bent at the other end of the test wire allowed the operator to hold the wire taut to ensure close adaptation to the mandrel during the wrapping procedure.

The length of the test wires needed to be approximately 310mm so that they could be subsequently tensile tested. Three wires were used for each test.

Method for wrapping procedure

Preliminary tests were performed on various batches of wires utilising the 38mm, 25mm, 15mm, and 10mm mandrels. Subsequent tests were conducted on the 10mm, 6.3mm and 3.23mm mandrels.

The mandrels were rotated at approximately one revolution per second. When the length of wire had been wrapped the mandrel rotation was stopped. The wire was then held in position for 30 seconds. The operator then placed the palm of his hand around the wrapped coil on the mandrel and allowed the coil to slowly unwind itself by gradually releasing the grasp on the mandrel. This was done to prevent the coil from springing back quickly and creating additional stresses in the wire. The locking screw was untightened and the coil removed from the mandrel.

Tensile testing

The apparatus utilised was an Instron tensile testing machine - Model 1114 with automatic graphing‡. A cross-head speed of 0.5mm/minute was employed to comply with Australian Standard 1964-1977. An Instron extensometer was used to measure the elongation of the wire specimen.

The wire grips were of a specially constructed wrap-around type to minimise the amount of stress concentration within each grip. In this investigation the longitudinal elements of the inner aspect of the wire are subjected to compressive stresses during the wrapping test and then subjected to stresses in the reverse direction during the tensile test.

Stress-strain graphs were produced to the point of fracture for the range of wires tested. The ultimate tensile strength, the 0.2% proof stress, elastic modulus and elongation at the point of fracture were measured from the graphs.

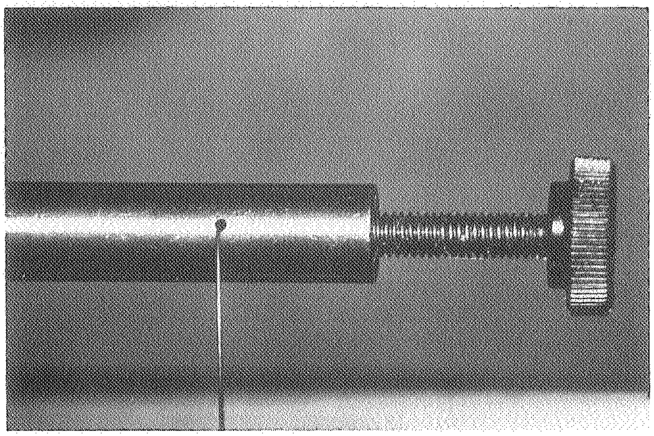

Figure 1. Wrapping apparatus

RESULTS AND DISCUSSION

The combined results of the preliminary and subsequent tensile tests on the three grades of 0.40mm (0.016") Wilcock stainless steel wire following wrapping around the various mandrel diameters are given in Tables 1-3 and are illustrated in graph form in *Figures 2,3,4*. Average values for each parameter are given.

It should be noted that wire samples in the preliminary studies are from a different batch from that used in the subsequent tests. This would account, to a large degree, for the difference in the 10mm mandrel values between the pilot and subsequent tests for the same grade of wire.

Pilot studies indicate that the tensile data from wires wrapped around the 38mm mandrel were similar to those from wires in the "as received" condition. It should be mentioned that these Wilcock wires are supplied on spools with an inner diameter of approximately 38mm.

With the 10mm, 6.3mm and 3.23mm mandrels, there was a significant reduction in tensile strength and 0.2% proof stress, and an increase in elongation. Also, despite a wide scatter of its value, there was a tendency towards a drop in elastic modulus.

The reduction in proof stress indicated that a significant Bauschinger effect occurred in these stainless steel wires, particularly following prestrains created by wrapping wires around the 10mm, 6.3mm and 3.23mm diameter mandrels. Also, increasing the level of pre-strain by wrapping around successively smaller mandrels increased the degree of Bauschinger effect observed.

The observation of an increase in elongation with increased Bauschinger effect noted in this study is in agreement with the findings of other authors (Polakowski,1966; Dieter, 1976).

However, the observed reduction in elastic modulus does not appear to have been previously noted in the literature. The scatter of its values again illustrates the *difficulty in accurately determining elastic modulus for orthodontic wires from tensile testing.*

Reduction in proof stress and Young's Modulus and increased elongation might be expected to have the following effects in the clinical situation:

1. The maximum stored energy (area under the elastic portion of the stress-strain curve) is reduced; thus the amount of available elastic energy for tooth movement is reduced. This results in a decreased amount of tooth movement.
2. The maximum force level that can be applied without plastically deforming the wire is reduced.
3. Within the elastic range, there is a reduction in the rate of change of force magnitude, that is, when an archwire is deflected, the force level remains more "constant" over a given distance. This is due to the lower stress-strain ratio (Young's Modulus).
4. The ease and precision with which a wire can be bent or shaped is increased due to greater ductility (elongation), that is, the formability of the wire is enhanced.

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* Protocol Engineering Ltd, Berkhamsted, Herts., U.K.
‡ Instron, High Wycombe, Buckinghamshire, U.K.
Note that there are also star asterisks in the tables

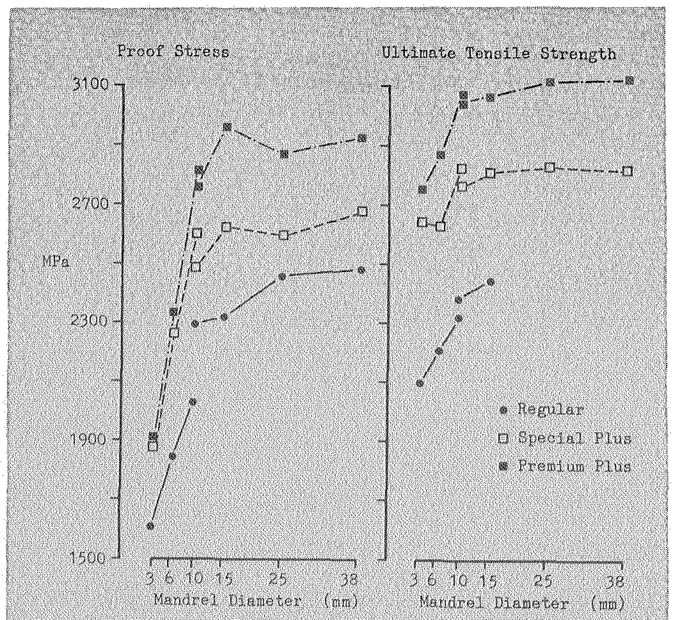

Figure 2. Change in tensile properties of various grades of 0.40mm (0.016") Wilcock stainless steel wires following wrapping over the 38mm to 3.23mm mandrel diameter range (combined data from preliminary and final investigations.

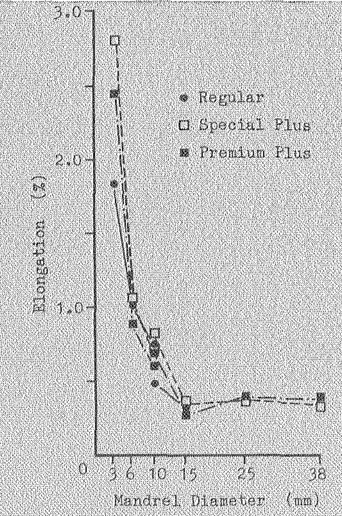

Figure 3. Change in ductility of various grades of 0.40mm (0.016") Wilcock stainless steel wires following wrapping over the 38mm to 3.23mm mandrel diameter range (combined data from preliminary and final investigations).

Some of these changes, such as increased formability, may be beneficial depending on the clinical application. However, generally, a reduction in maximum stored energy is undesirable.

CONCLUSION

Wire samples that had been prestrained by wrapping procedures were tensile tested to evaluate the Bauschinger effect. The results indicated that a significant Bauschinger effect occurred resulting in a reduction of the elastic potential of the wire. Thus in the clinical situation, the orthodontist can make best use of the elastic properties of a wire and achieve maximum displacement of a tooth by activating or deflecting a wire in the same direction as the original curvature in the wire. One such example is *when loops or springs are to be constructed they should carry their load in the same direction as that in which they were wound or formed.* However, in some situations, such as the formation of anchorage bends or curves, it is impossible to avoid reverse bending. One way of minimising the deterioration in elastic potential under reversed stress would be by a stress relieving heat treatment. This would eliminate a great part of the internal stresses that are responsible for the Bauschinger effect. However, *when clinicians have a choice, they should use a design that loads the wire in the direction of forming.*

Finally, it should be noted that the conclusions made in this study are based on trends observed following tests on relatively small sample numbers. Further tests on a broader statistical basis are necessary before firm conclusions can be drawn.

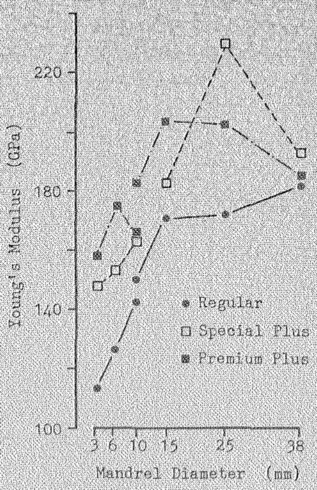

Figure 4. Change in Young's Modulus of various grades of 0.40mm (0.016") Wilcock stainless steel wires following wrapping over the 38mm to 3.23mm mandrel diameter range (combined data from preliminary and final investigations).

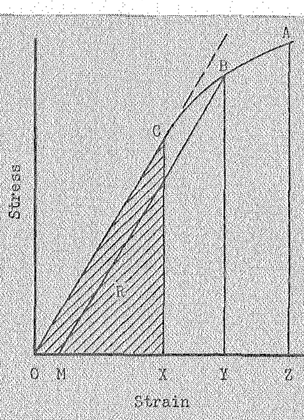

Figure 5. Stress-strain graph for a high tensile wire

Table 1. Tensile test data for .40mm (0.016") Regular Wilcock stainless steel wire following wrapping

Mandrel Diameter (mm)	Proof Stress 0.2% (MPa)	Tensile Strength (MPa)	Elongation (%)	Young's Modulus (GPa)
38	2480	*	*	182
25	2459	*	*	172
15	2324	2441	0.32	171
10	2293	2386	0.49	150
10	2028	2322	0.75	143
6.3	1844	2204	1.00	126
3.23	1605	2094	1.83	114

* early fracture

Table 2. Tensile test data for 0.40mm (0.016″) Special Plus Wilcock stainless steel wire following wrapping

Mandrel Diameter (mm)	Proof Stress 0.2% (MPa)	Tensile Strength (MPa)	Elongation (%)	Young's Modulus (GPa)
38	2679	2825	0.33	193
25*	2597	2835	0.37	230
15*	2624	2819	0.32	183
10*	2484	2769	0.81	119
10	2600	2824	0.68	165
6.3	2259	2631	1.00	154
3.23	1879	2648	2.91	148

* single test sample

Table 3. Tensile test data for 0.40mm (0.016″) Premium Plus Wilcock stainless steel wire following wrapping

Mandrel Diameter (mm)	Proof Stress 0.2% (MPa)	Tensile Strength (MPa)	Elongation (%)	Young's Modulus (GPa)
38	2933	3131	0.37	185
25	2876	3122	0.39	203
15*	2963	3073	0.29	204
10	2761	3051	0.68	184
10	2816	3063	0.61	165
6.3	2336	2866	0.88	175
3.23	1899	2753	2.45	158

* single test sample

REFERENCES

BURSTONE,C.J..(1985)
Application of bio-engineering to clinical orthodontics.
In: Graber,T.M. and Swain,B.F., eds. Orthodontics - Current Principles and Techniques. C.V.Mosby Co., St. Louis, p.203
DIETER,G.E.(1976)
Mechanical Metallurgy.2nd edition.
McGraw-Hill,Inc.,New York.
INGERSLEV,C.H.(1966)
Influence of heat treatment on the physical properties of bent orthodontic wire.
Angle Orthod.36:236-247.
OROWAN,E.(1959)
Causes and effects of internal stresses, In:Internal Stresses and Fatigue in Metals, eds.,Rassweiler,G.M.
and Grabe,W.L. Elsevier Publishing Co.,New York.
POLAKOWSKI,N.H.(1966)
Strength and Structure of Engineering Materials.
Prentice-Hall,Inc.,Englewood Cliffs,New Jersey.
WARE,A.L. and MASSON,R.J.(1976)
Physical properties of orthodontic wires.
Aust.Orthod.J.4:53-61
WATERS,N.E.(1972)
A method for characterising the elastic deformability of orthodontic wires.
Dent.Practit.22:289-295

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