THE INVESTIGATION INTO THE MECHANICS AND INDUCEMENT OF RESIDUAL TORSION WITHIN THE BEADWIRE PRODUCTION PROCESS

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FOR THE DEGREE OF

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ASTON UNIVERSITY, BIRMINGHAM

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Aston University Birmingham

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SUMMARY

National-Standard Co. Ltd. senior management recognised the need to meet the increasing standards in quality being set and demanded by the tyre and automotive industries for products and components being supplied to them for the 1990's.

A 2 year project was initiated to investigate the Beadwire final processing and control, to reduce the effects of residual torsion (axial twist) and identify the influences of various elements within the process which affect the quality of the wire, so enabling improved control on product variability and overall consistency.

The main phase of the project has been to determine the cause and define the mechanics of residual torsion within the final production process. A theoretical mathematical model of the process showed that there was a connection with the material physical properties i.e. wire diameter & ductility but there was a combination of outside factors that could also influence the amount of residual torsion within the wire. The main significant conclusion formed was that residual torsion phenomenon is elastic in nature rather than a plastic deformation problem.

Further experimental work was conducted on the straightening rollers, as this was the only position within the process where the wire could be monitored, travelling at 4 m/sec. This highlighted the main factor affecting the process as wire tension, which influences the control of residual torsion within the straightening rollers. Design & implementation of a pneumatic tension control for the let-off system established the improvement in residual torsion control through the straightening rollers.

Key Words : Torsion, Wire, Twist, Axial, Straightening

DECLARATION

No part of this work has been submitted in support of an application for another degree or qualification of this or any other university or institution of learning.

Andrew Nicholas Hindle. B. Eng.

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To Mr Allen Hopkins (Managing Director) for allowing the Teaching Company Scheme to operate within National Standard Co. Ltd.. To all the personnel at National Standard Co. Ltd. for their support, guidance and friendship throughout the 2 years of the project.

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Chapter 1

Introduction

The request for a Teaching Company Scheme (TCS) to be established at National Standard Company Ltd. was initiated by senior management in recognition of the need to meet the changing wire industry environment forcing National Standard to improve their competitiveness. The requirement for new technical skills and investment in more advanced technologies was recognised to increase the standards in wire quality being asked for by the tyre and automotive industries but there were several factors that restricted progress :

- Capital Investment Funding
- Staff to conduct research and development
- Access to expert knowledge and help

The TCS is designed to introduce graduate engineers, with financial support from the government, into industry to undertake high profile projects and enhance the competitiveness of business by building technology transfer partnerships with universities.

The objectives of the scheme are:

- To facilitate the transfer of technology and the spread of technical and management skills and to encourage industrial investment in training, research and development.

- To provide industry based training, supervised jointly by academics and industrial staff for young graduates intending to pursue careers in industry.

- To enhance the levels of academic research and training relevant to business by stimulating collaborative research and development projects and forging lasting partnerships between academia and business.

The support from the university gives practical guidance in the selection, implementation and development of technology, supports the direction and management of the project and assists in the development of the Teaching Company associate in their development within the company.

An assessment of National Standard's four core products; Beadwire, Hosewire, Weldwire and Copperply was undertaken by the management team in conjunction with Aston University, as to which products to develop and to target specific quality issues within the wire processing and control. Three separate projects were devised and approved to run at National Standard, investigating significant aspects of wire production process. The subject of this thesis is one of the projects investigating the final processing and control of tyre beadwire.

The beadwire within a car and aircraft tyre, (for a description of tyre beadwire see Chapter 2), is one of the most critical components, giving re-enforcement to the tyre edge as it sits on the rim of the wheel. Over the last 30 years the Wire and Tyre Industries have been troubled with problems with the tyre bead twisting / kinking either when the bead is formed into a hoop of wire covered in rubber compound or as the tyre assembly in being cured. During the late 1980's Tyre Manufacturers expressed the view that the quality of the wire used was becoming a matter of great concern and consequently that there was a definite need for all wire producers to improve their quality performance. Simply meeting existing standards was declared to be inadequate.

The twisting / kinking of the tyre bead has been found to be connected with high residual torsion within the wire. The phenomenon residual torsion has been termed 'Axial Twist' within the wire and tyre industries, occurs as the wire is being processed and results in a radial twist along the longitudinal axis of the wire. The term 'Axial Twist' will be generally used to refer to 'Residual Torsion' throughout this thesis.

Over the last 10 years National-Standard Company Ltd have been investigating axial twist to try and reducing the amount of twist found in the wire by varying or altering different parts of the production process. They have found that they have had varying degrees of success, reducing the overall variation of axial twist from +/- 5 turns to +/- 1.5 turns measured over a 9.1m (30 feet) length of wire. Currently the product specification is a twist within the wire of up +/- 1 turn per 9.1 meters and as part of their drive for greater product quality for the 90's, National Standard have set out to reduce and control axial twist to within +/- 0.25 turn by the year 2000.

The main goal of this project is to find a way to reduce the twist within the tyre beadwire. This will be done by :

- Listing all of the possible causes - Reviewing the company documentation, the wire drawing & plating processes and dissecting customer tyre beads.

- Understanding the related theories - Reviewing the significant parameters affecting axial twist by using Taguchi modelling technique.

- Modelling the process - Building a theoretical calculation of how axial twist is induced within the wire using simple torsion theory and determine the relationship with the wire's modulus of rigidity.

- Conducting experiments - Modifying a set of straightening rollers to incorporate load cells to enabling the load applied to the wire to be monitored as it is processed and conducting a designed experiment using Taguchi modelling technique.

- Deriving the main cause of axial twist - From the results of the experiments highlight that tension of the wire as it is processed is the main factor contributing to the inducement of axial twist.

- Modifying the production equipment to prove improvements give the desired results in production - Modifying the wire let-off system, replacing a simple spring mechanism with a pneumatic cylinder to control wire tension and establishing tension as the key to the control of axial twist.

The targeted practical outcome of this research is to improve control of axial twist within the wire, so increase product consistency, reduce the reworking of the wire & associated manufacturing costs and improve the wire quality.

CHAPTER 2

NATIONAL STANDARD & TYRE BEADWIRE

2.1 Company Background

National Standard was formed in the USA early in the 1900's with the incorporation of two companies, National Cable and Standard Wire Manufacturing Company. Later in 1913, they acquired the Cook Standard Tool Company.

It was not until 1929 that a facility was opened in the United Kingdom, in Stourport-on-Severn, as a partly owned subsidiary of the National Standard Company of Niles, Michigan, USA.

The main product of the company at that time was braided wire for use in the beads of pneumatic tyres. In practice supplies of coated high carbon wire were bought in and only the braiding operation was carried out in-house. In 1938 a galvanising and electroplating plant was installed, which enabled National Standard to produce its own zinc and copper coated high carbon steel wire for braided, taped and single strand beads.

After 1946 business began to grow as the demand for automobiles increased. This in turn, led to the company relocating to a site in Kidderminster. By 1949 the company was operating at full capacity with record sales being achieved. In 1955 the present day site was acquired, to enable the company to expand via the building of a more modern and larger plant. Production commenced in 1956 and since then capacity has been extended through significant investment in plant and machinery.

In 1960 the company became wholly owned by the American parent and by 1964 a new plant had been built at Llanelli, South Wales, manufacturing tyre bead production machinery.

During the 1970's the company expanded further with the introduction of two new manufacturing operations, the first at Telford, Shropshire and the second at Perth, Scotland. By the late 1970's, National Standard employed 1000 people with the Kidderminster facility as the Head Office for the United Kingdom operations. At the same time the operations at Llanelli were closed down and the machinery division was transferred to a new unit in Telford.

In the 1980's, the business climate within the wire industry changed with the Telford wire making division being forced to withdraw from the volume manufacture of tyre cord mainly due to competitive pressures and adverse sterling exchange rate. The Perth facility continued to develop with a move into hydrostatic extrusion. The product portfolio included, copper covered aluminium, bar rod and wire, aluminium machining rod and forging and aluminium welding wire.

Prompted by the 1990's world wide recession, the parent company saw the need to take positive action by re-organising and streamlining its operations throughout the organisation on its core activity of wire products. By 1994 the Kidderminster had become the sole facility in the United Kingdom.

2.2 Core Products : Descriptions

1) Hydraulic Hose Wire : Such wire is used in the reinforcement of high pressure hoses and is manufactured in sizes from 0.25 to 0.77 mm diameter and has a tensile strength up to 3300 N/mm^2 (215 T/in^2).

2) Welding Wire : Weld wire is used in gas shielded welding operations and is produced in two forms: copper coated and copper free. The Company specialises in copper free wire which in certain countries is regarded as a superior product due to an increased reduction in dangerous and health threatening fumes.

3) Copperply : This is used in telephone line wire, telephone drop wire, railway cantenary strands (supporting overhead conductor) and is used in the production of fine wire for the electronic industry. The wire is produced by electro plating a thick deposit of copper onto steel wire.

4) Tyre Beadwire : Two basic grades of tyre beadwire are produced: Standard and High Tensile. Both grades are hard drawn bronze plated steel. High Tensile is used for special purpose tyre construction, such as civil and military aircraft and other high performance applications. Standard tensile wire is used in passenger and commercial vehicles and is supplied to all United Kingdom based tyre companies.

2.3 Tyre Bead

The tyre bead is a term which refers to the metal reinforcement in the tyre, which is more correctly termed the 'grommet' or 'bead grommet'. It is a steel ring composed entirely of wire strands[1].

A tyre cross section resembles the shape of a horseshoe with the bead forming both ends or heels. The bulk of the tyre section is made up of textile material, such as cotton and rayon, is intermixed with vulcanised rubber compound. The rubber compound extends all around and over the side walls to form a shield protecting the fabric interior. At the tyre edges, a triangular shape formed from the bead or beaded edges allows the tyre to be placed onto the rim. (see figure 1).

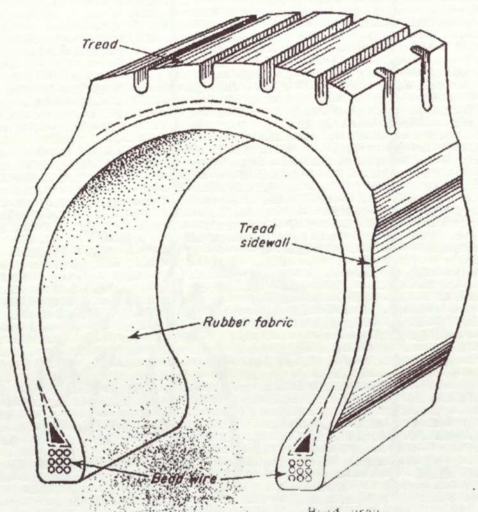

Figure 1 : A cut cross section of a pneumatic tyre.

The bead in the modern straight-sidewall tyre holds the casing onto the rim by preventing edges of the tyre from stretching. Without the support and structural rigidity given by the wire the pressure of the air inside the tyre would cause the edges of the casing to stretch over the rim of the wheel flanges. The ridged nature of the beaded wire ring transfers the load on the tyre to the wheel flange edges.

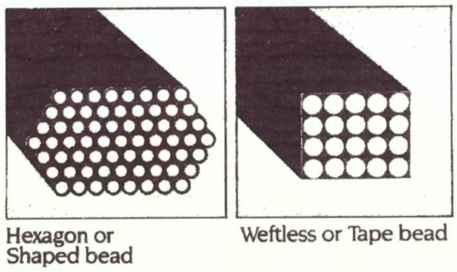

Figure 2 : Illustration of two types of tyre bead.

The bead in tyres can be made in several forms (see figure 2);

1) 'Single' - A single stand of wire, covered in a compound of rubber, wound around a former to produce a stranded, ring shaped bead.

2) 'Weftless' - Several parallel stands of wire, covered in a compound of rubber, (which produces a tape of wire) is wound around a former to produce a stranded ring of wire.

The bead is considered as the foundation of the whole tyre construction and the taped steel rings of steel wire allow a secure anchorage for the layers of textile material which are used for the body of the tyre (see figure 3).

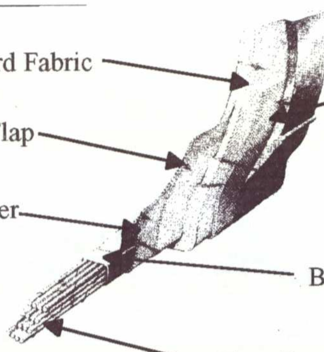

Figure 3 : A sectioned picture of a tyre beaded edge, illustrating the bead construction within the wall of the tyre.

2.4 Axial Twist and its affects on Tyre Manufacture

Axial twist is a radial twist which is found to be present within the thin diameter beadwire after the wire has been plated with a bronze coating. The amount of twist present in the wire is measured after each reel of wire has been plated and is found to exist in either a clockwise or anticlockwise direction.

The actual method of measuring axial twist consists of bending the wire at right angles to its axis, pulling the wire out from the reel to a length of 9.1 metres, then releasing the wire bent at a right angle, while holding the extended length of wire. The amount of twist within the wire is found by watching the end of the wire rotate, either clockwise or anti clockwise.

The bead becomes vulnerable to axial twist amid two phases of the tyres construction; the bead formation and during the tyre vulcanisation process. During the manufacture of the bead, if the beadwire used contains high axial twist this can affect its construction in two ways. Firstly the end of either the inner or outer wire, in-cased in rubber compound, of the layered bead tape, can break away from its neighbour. The bead construction becomes a reject due to the detached wire degrades the bead formation. The strength of the bead is derived from the wires being tightly packed together and this is reduced if the bead wires start to separate. Secondly the whole round bead construction can twist and kink forming a type of figure of eight shape. This formation stops the bead from being able to be assembled into the tyre construction before vulcanisation.

The bead also becomes vulnerable to axial twist during the vulcanisation process to form the tyre. As the tyre is heated within the press under high pressure, the rubber becomes soft before its is vulcanised, it is at this point the that a wire at the edge of the bead construction can become detached and protrude through the tyre wall. The tyre is rejected due the poor quality, cosmetically for the wire protrusion and for the tyre performance being degraded due to the reduced strength of the tyre wall.

Chapter 3

Prior Work and Literature Survey

3.1 Introduction

It was necessary to review what the nature and outcomes of research which the company had previously undertaken to assess the extent of the internal problem of axial twist. In addition a literature search to review any theoretical / technical papers published in connection with residual torsion / axial twist was conducted at Aston University library computer data base.

3.2 Company Documentation

Over a four year period, between 1988 and 1992, a common conclusion within the company, in both the UK and USA on the problem of axial twist was that it was caused by a physical deformation of the wire, during processing. Within inter company communications and reports, potential areas were highlighted and numerous attempts were made to eliminate the problem from the production process.

General opinion was that the processing of the wire through the heat treatment process 'the Lead Pot' (a lead bath, at a temperature of 570 degrees C) had a direct effect on the ability of corrective devices (i.e. straightening rollers, attached to the end of each wire processing ends), to be able to reduce and eliminate axial twist from the wire during processing.

In 1989 a Beadwire Task Force was established between the facilities within the parent company in the USA and included personnel at Kidderminster. Their objective was to 'determine the effect of various beadwire plating line and straightener system factors on the control of cast, helix and residual spins (twists) in beadwire'. In March 1989, the minutes of the task force meeting[2] highlighted that the team had produced through a brainstorming session, an extensive list of factors thought to influence the processing of the wire and induced axial twist. The main factors being:

1) Lead pot wire entry and exit sinkers,

2) In-line wire let-off system,

3) Wire diameter variation,

4) Starting wire cast,

5) Bright wire quality,

6) Straightening rollers and block orientation,

7) Pulley diameter,

8) Wire mechanical properties.

An experimental strategy[3] was set up to assess the factors (listed above) that might influence axial twist during processing of the beadwire. A decision was taken to set up a series of experiments, assessing the effects of line and straightener variables.

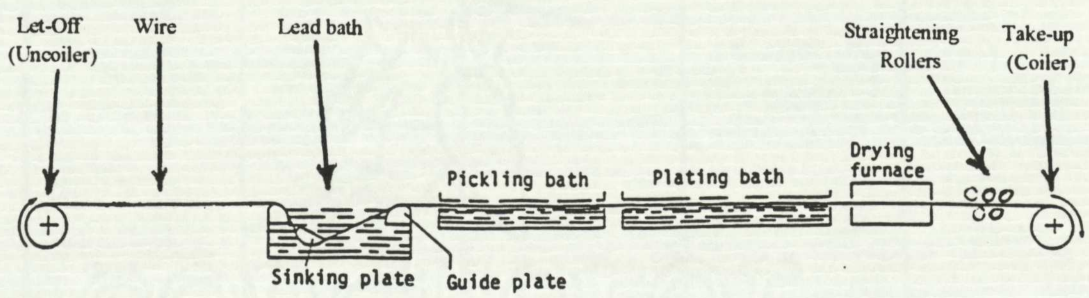

Figure 4 : An illustration of a continuous beadwire plating process line.

A number of line trials were conducted in the USA investigating the effects of changes in :

- The position or angle of the 'lead bath' wire entry and exit sinkers and the type of materials that could withstand ware and long exposure to high temperatures.
- Types of guide rollers used.
- Straightening the wire at beginning of the plating process.

The main conclusions from these experiments were :

- That the alignment of the sinkers, the U groove guide runners into, through and out of the lead bath was extremely critical.
- That a radius of 254 mm (10 inches) for the sinkers was the optimum to achieve significant improvement for all characteristics.
- Axial twist was found to be consistent throughout the experimental reels of wire.
- Straightening rollers : rollers set at the beginning of the plating process did not have significant influence on the process and were not required.

At Kidderminster a report on 'Axial Twist Evaluation'[(4)] was produced in May 1989 and gave a summary of meetings and experimental work carried out over a three year period up to May 1989. The report made a number of attempts to clarify the extent of the variability of axial twist within the beadwire process and to detail results found after wire final processing and reject returns from tyre manufactures.

Conflicting results were found as to the extent as to how much wire diameter ovality played a part in the inducement of axial twist. The reports summarised that ovality of three microns to over twenty seven microns (specification of +/- 10 microns) were found within 450 Kg reels of wire which exhibited an axial twist of greater than +/- 2 turns over 9.1 meters. They also highlighted instances of satisfactory reels of wire being produced prior to an unsatisfactory reel and visa versa, produced under the same production conditions.

The reports conclusions, could not positively identify that wire ovality had an overriding affect on axial twist, proposing further work to be conducted to find a solution(s) that would produce a twist-free wire consistently.

From December 1989 and for a further two years, internal correspondence by the task force team continued detailing their ongoing investigations and reports into the factors which influenced the final drawing and processing of beadwire. Their main recommendation during this period, to reduce axial twist, was to improve the design of the lead bath sinkers[5&6] in the belief that axial twist was being physically induced by the action of being pulled over a surface or pulley. Implementation of an modified sinker design found that during the trials, under controlled experimental conditions, axial twist was reduced but when introduced under general production conditions, previous unacceptable levels of axial twist variation returned.

The final recommendation made by the task force team was that the investigation into axial twist should be continued and that it was necessary to understand how to control the erratic levels of twist within a reel of wire.

3.3 Technical Papers

The main area of the literature search concentrated on journals published within the wire industry; Wire Industry, International Metals Review and Wire Journal International.

Searching through the Aston University library database it became apparent that there was very little published work on the problem of residual torsion or axial twist within the wire industry. Publications on the fundamentals of wire drawing and conditioning, material composition and handling were abundant

A search reference on torsion found a paper on 'Torsional Ductility' [7] which was concerned with the reasons why different diameters of wire exhibit relatively poor torsional ductility but the work was however concerned with large diameter wires and not connected with axial twist as found in small diameter wire. This was typical of any connection made with key words used in the database search.

The only research paper found on the final processing of beadwire was by 'Motoh Asakawa and Chuzo Sudo' [8] from Sumitomo Metal Industries, Ltd., Japan. Their research dealt with the effects of cast and helix formation within the wire, after plating, which causes the wire to bend or become curved. They examined the effect of two dimensional wire curvature down the process line and used quantitative analysis to analysis theoretical and experimental data in an attempt to evaluate three dimensional curvature wire. Within their paper they examine the affects of 'spin' (axial twist) upon the curved wire.

Asakawa and Sudo make several observations from their results :

- During the formation of axial twist the wire is deformed plastically with torsion.
- After stress relieving through the bluing bath (lead pot), the wire may have been given new bend and twist by the sinking or guide plates.
- The wire is given various torsional moments by the roller straightener, guide rolls, un-coiler and coiler.

The above observations would seem to be consistent with the experimental work carried out by the National Standard task force team, in that the perceived plastic deformation being applied to the wire throughout the process. As the wire moves over and around the various guides and rollers it is concluded that at these points, as the wire comes into contact with the process that a twist is physically induced into the wire, either clockwise or anti clockwise rotation and is responsible for the degree of axial twist found in the finished product.

They concluded that 'it is not always clear why the wire must spin while it passes through the plating process lines. More detailed research is required'. Its from this statement that the research described in this thesis progresses.

3.4 Discussion

The experimental work carried out by National Standard in both the USA and UK highlighted that the task force team did not have a full understand of the process and interactions that combine to produce axial twist within a reel of wire.

Throughout the search of company documentation, each detailed investigation has used a common approach of looking at a single element of the process at a time. This has lead to implementation of improvements, demonstrated as an effective solution to the problem under controlled experimental / trial conditions but has ultimately not permanently corrected the problem running under normal production conditions. The whole plating process requires to be investigated and the complex relationships between the output and its input parameters mapped and understood. Common elements require to be highlighted and minor interactions be eliminated from an experimental model of the process being investigated, giving a clearer understanding of the factors that influence the output the engineers were trying to control.

It became apparent that the engineers at National Standard did not have a clear understanding of the output factor axial twist, so did not considered all processing implications that could effect the wire as it travelled down the plating process. This type of experimentation can be generalised as 'one factor at a time' approach[9] and in doing so they concentrated on one particular section of the process, the 'lead bath' and made a general assumption that the plating baths, pulleys & guides, the straightening rollers and the take-up coiler had a reduced effect in inducing axial twist in the wire.

The problem with one factor experimentation is the inability to clarify the nature of the interactions among the key factors within the system or process being investigated and leads to a high degree of guesswork when dealing with a complex system. The interactions are the elements that need to be understood when conducting an analysis on a process, by studying and understanding a system or process properly, understanding the inputs and outputs, the true root cause of a problem can be determined and enable the process or system to be correct and optimised.

The single technical paper found on the effects of cast and helix formation to the wire which causes the wire to bend or become curved during plating has illustrated the amount of knowledge there is within the industry and the need to conduct more research into wire processing. The dynamics and characteristic of wire reduction has had a general fascination within mechanical engineering community and this is highlighted by the abundance of published work into the subject. The manufacturing or processing side of a product has generally taken a back seat but in today's competitive climate, it is now just as important that a quality product is produced on time and at the lowest cost.

The abundance of material on the drawing down of wire, there effects and the final properties obtained, hampered the search process. Each paper found on or connected to wire drawing had to be reviewed for any reference or connection with axial twist. The absence of research material and data, initially made it difficult to formulate an action plan, where could the investigation start? How could we track and measure axial twist within the wire drawing and plating process?

The single published paper into the plating of beadwire has turned out to be an advantage for the project. To investigate and acquire a complete understanding of the cause of axial twist, the investigation must go back to basics and look at the process using first principles. Permanent quality improvement within the process cannot be successfully implemented without a complete understanding of all the parameters (factors) which inter-react to produce the output (response factor) of axial twist.

Chapter 4

Beadwire Production Process

4.1 Introduction

The actual method of drawing wire is simple. It is a process of reduction to decrease the diameter or cross sectional area until the required size or diameter of wire is achieved. The practical skill (black art) of wire drawing, which derives much of the complexity in the complete process, is to produce the finished wire product with the required mechanical specification.

The carbon content of the raw steel together with its intended end use and the final mechanical specification of the product, determines the degree of reduction under gone by the wire at each individual stage of the process and the type of processing undergone to achieve the final product. The die reduction practice / selection is determined by the important 'Hardness Factor' calculated from the amount of carbon (C) & manganese (Mn) present within the steel chemistry. This factor is used to select the start size of the secondary or final drawing stage which then determines initial die practice.

Hardness Factor (HF) :

$$HF = (\%Mn/5 + \%C) \times 100$$

Where - Mn : Manganese, C: Carbon
Note : If a HF lies between 2 start sizes, select the largest size.

From this calculation the ratio of each die reduction for each stage of the process is obtained.

Beadwire Process Flow

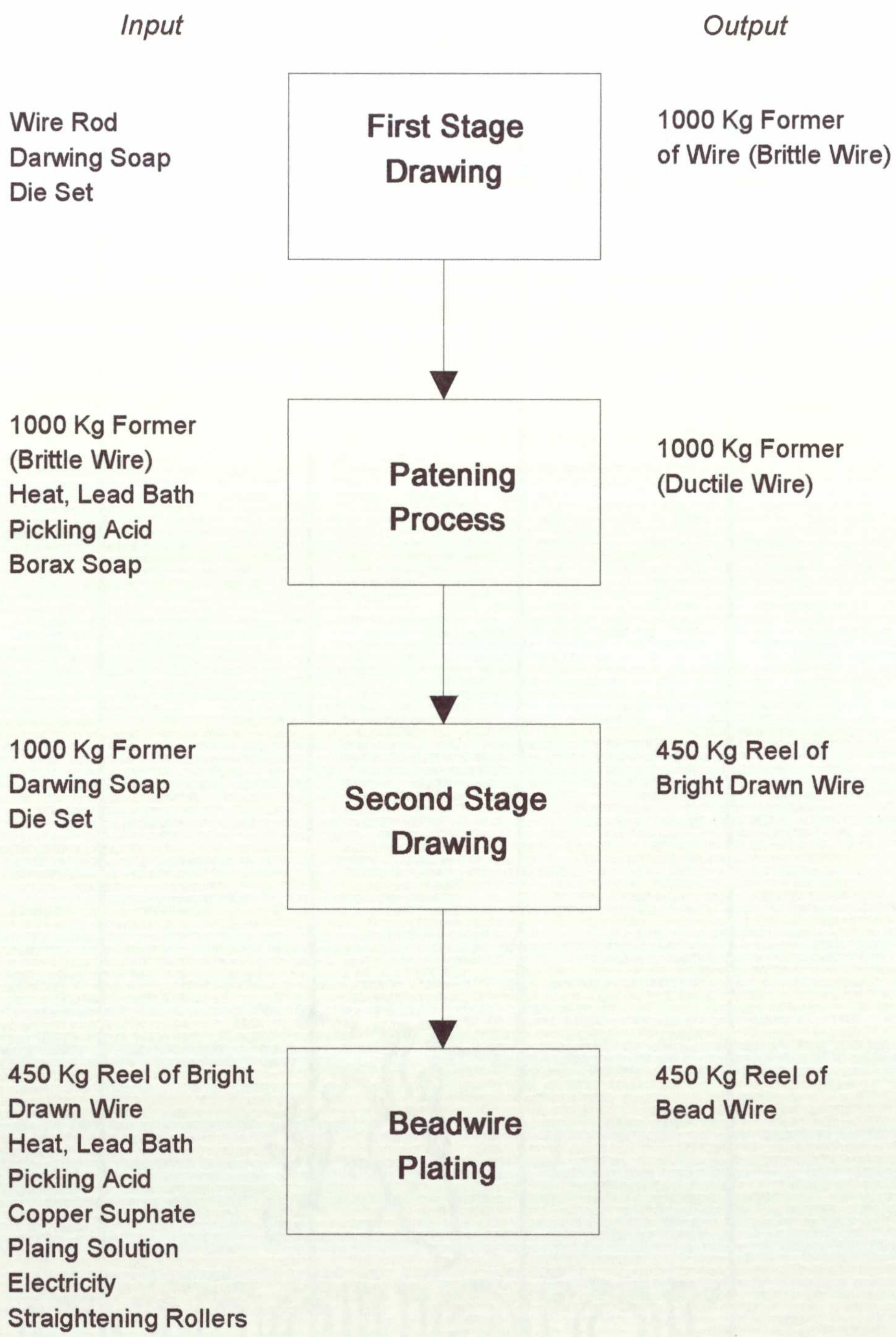

Figure 5 : Beadwire process flow diagram - Inputs and outputs of the beadwire drawing process.

A typical cast analysis of material for 0.965 mm Standard Beadwire is : 0.65% C, 0.22% Si, 0.59% Mn, 0.014% P, 0.016% S, 0.008% Cu, 0.022% Ni, 0.031% Cr, 0.004% Mo and 0.002% Sn. A typical hardness factor for a 0.65 % carbon steel would be 76.

Hardness Factor (HF)	Start Size (mm)
73	3.5
74	3.5
75	3.45
76	3.45
77	3.4
78	3.4
79	3.35
80	3.35
81	3.35
82	3.35

Table 1 : Typical hardness factors and start sizes for 0.965 mm standard tensile steel wire with a standard carbon content of 0.65%.

4.2 First Stage Drawing

Once the die sequence has been determined, the reduction process starts with wire rod of 5.5 mm diameter, wound in 1.5 tonne coils, first being dried to remove any surface moisture (which affects the dry soap lubrication). The first stage drawing, 'Breakdown' of the wire from 5.5 mm is dependent on the number of dies indicated by the hardness factor e.g. typically 3 or 4 dies for beadwire, achieving a reduction in the range of between 3.4 and 4.4 mm, with higher carbon steels requiring 4 die passes due to the higher carbon content.

As the wire is reduced through the first die, the wire is drawn or pulled by a large diameter block which also cools the wire as heat is generated in the reduction process. From the block, the wire passes over and through a series of pulleys to bring it in-line with the next die box and reduction pass. This is repeated down through the series of 3 or 4 dies until finally it passes through a re-coiling machine which puts a cast, of around 36 inches, into the wire to allow the wire to be collected onto a upright former.

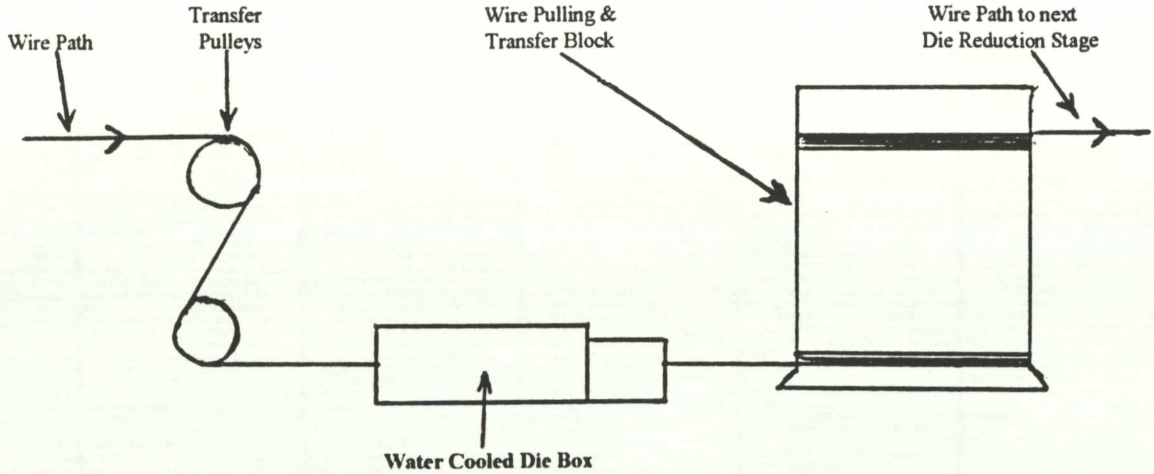

Figure 6 : First drawing stage - wire path through a die reduction stage.

By this stage the wire has undergone severe work hardening. The wire material now exhibits a long pearlitic grain structure and has become brittle. If a further reduction in diameter was attempted the wire would break after the first die reduction.

4.3 Patenting

The second stage in the wire drawing process is 'Patenting' of the reduced wire rod. The rod passes through a heat treatment process to make it more ductile, together with the addition of lubricants to aid the second stage of the wire diameter reduction.

The former of wire is placed onto rotating left-off stands which allow the wire to be pulled off the former without incurring a twist within the wire. The wire rod is first pulled through a 4 zone furnace which heats the wire to a temperature in excess of 1000°C. The actual 'patenting' process is the controlled cooling of the wire rod through the Time Temperature Transformation [10] curve to allow the grain structure within the metal to remain pearlitic and the material to become ductile. This is achieved by submersing the wire rod in a bath of molten lead at 570°C for a specific period of time which cools the wire at a regulated rate allowing a uniform pearlitic microstructure to form.

The patenting process line at National Standard is constructed in a 'horse shoe' shape in which the wire rod doubles back through a sets of pulley wheels for the second part of the process. In the second phase of the process the wire rod is first cleaned in sulphuric acid (to remove any surface scale or loose particles) which microscopically etches the surface of the wire rod. The acid is then washed off through a series of water baths, the wire rod is then passed through phosphate & borax coating baths, to improve the 'drawability' during the secondary, 'final', drawing stage and then soap is applied to assist the re-cast on to a former.

4.4 Final Drawing

The patented wire rod is now ready to be drawn down to its final size, of between 0.89 mm to 1.8 mm diameter, through another series of dies between 9 to 11 dies before being wound onto large (450 kg) steel reels.

The wire rod is pulled off the former through a rotating guide arm and then passed through a tension unit which allows the patented wire to be pulled through the first die at a constant rate. As in the first stage drawing process, the wire is pulled through the die box by a rotating block but each of the stations in the secondary drawing stage have a second rotating block mounted on top of the first (see figure 6). The wire is pulled onto the rotating block in a anti-clockwise direction then passes through a 'half way' wheel to reverse into a clockwise rotation, as illustrated in figure 7. Once the wire has reached a specific height on the second block, it is pulled off and over several pulleys which bring the wire back down and inline with the next die box for further reduction. Each drawing block is water cooled to remove the heat generated during each reduction through the dies.

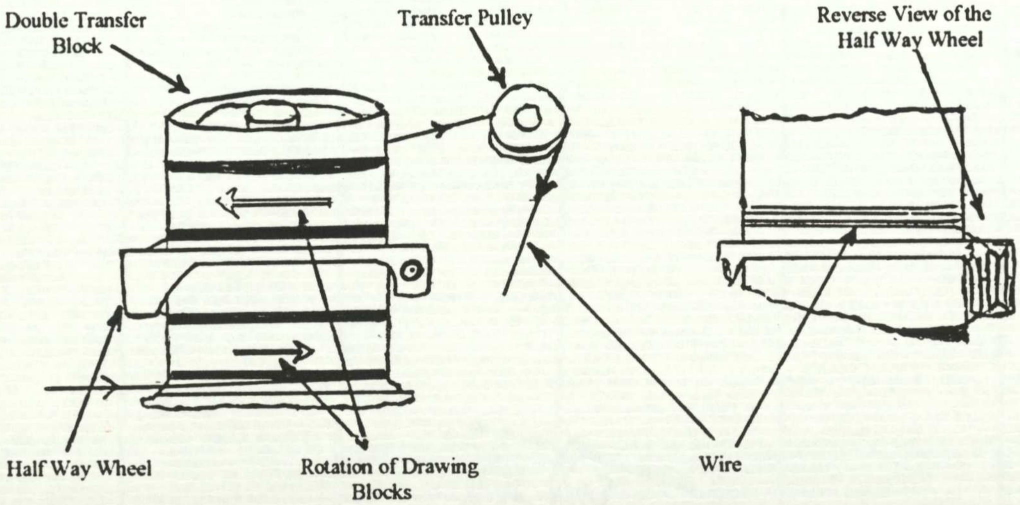

Figure 7 : Second stage drawing block wire transfer method.

Finally, after passing through the final die and onto the drawing block, the wire is pulled through a set of straightening rollers and then wound onto 450kg steel reels, with the bright drawn wire reaching speeds up to 1300 meters / minute (4000 feet / minute). The wire drawing reduction process is now complete.

4.5 Plating Process

The final process in the production of beadwire is the plating line: the wire is cleaned and plated with a bronze coating (several microns thick) via an electrolytic plating process. This plating is essential to allow rubber tyre compound to adhere to the wire (as rubber does not adhere readily to steel).

The wire is unwound from the 450 Kg reel through a let-off stand, (see figure 8), through a set of two pulley wheels in a 'figure of eight' configuration. This acts as part of the breaking system, maintaining a constant wire speed and tension. It is then is directed down the plating line via a third pulley.

The wire first passes through a 570°C lead bath which 'Stress Relieves' the wire, modifying the mechanical properties by increasing the ductility from 2% to 7% and reducing the breakload by 9%, (see table 2). This process also cleans off any residual soap that may be on the wire surface from the final drawing process.

	After Drawing			After Plating		
Wire Dia. (mm)	Tensile Strength (N)	Yield Strength (N)	Elongation (%)	Tensile Strength (N)	Yield Strength (N)	Elongation (%)
0.965	1400	1300	2	1300	1200	7.5

Table 2 : Typical mechanical properties of 0.965 mm beadwire before and after stress relieving through the lead bath.

The wire then passes through a series of tanks. The first cleans the wire using a caustic solution. The second comprises a sulphuric acid bath which pickles the surface of the wire.

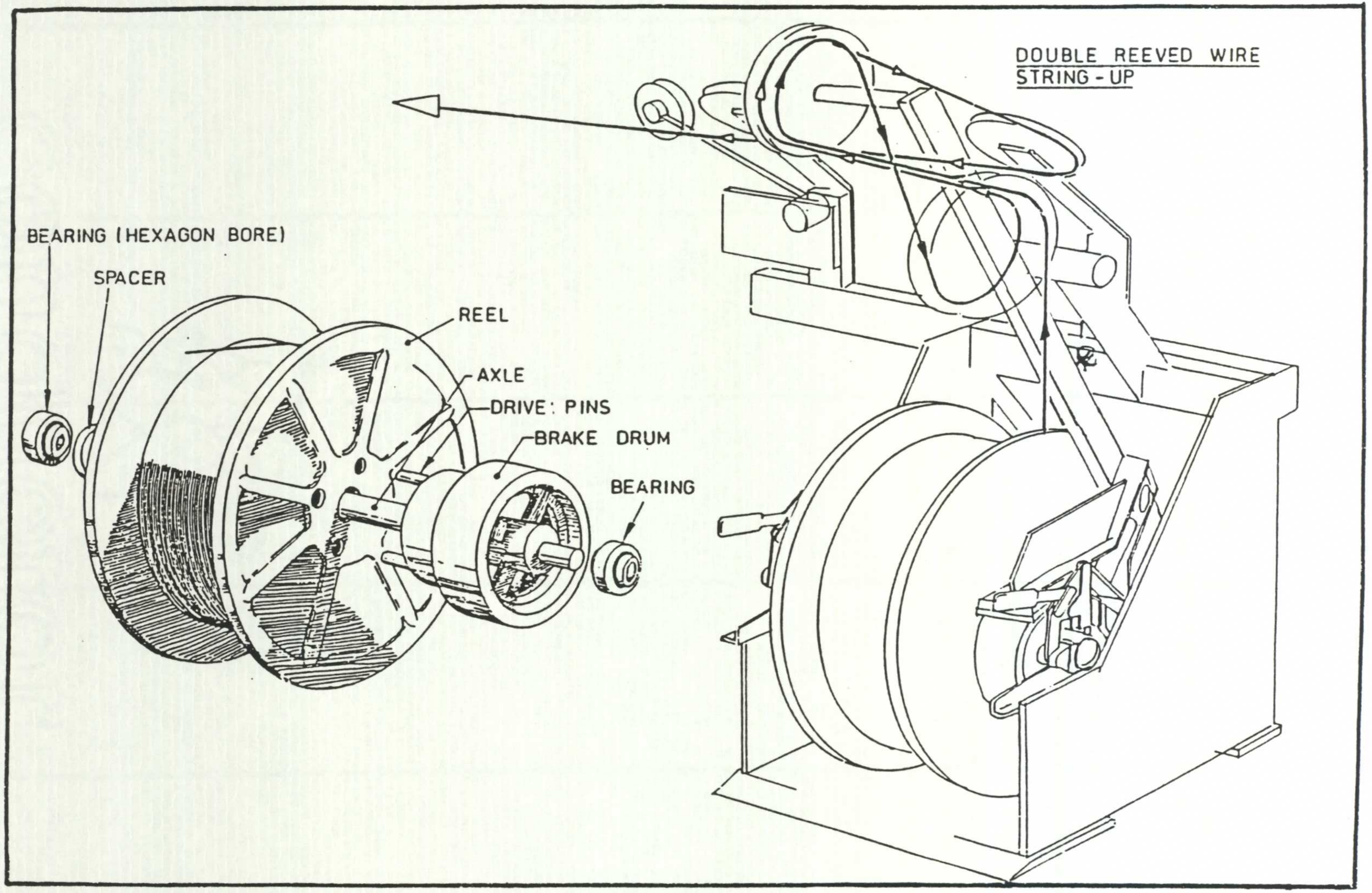

Figure 8 : An illustration of the let-off and braking system (un-coiler) at the beginning of the plating process.

Finally the wire passes through a plating solution made up of sulphuric acid, copper sulphate and stena sulphate (a solution of tin) to provided the wire with a coating of bronze comprising of approximately 98% Cu (copper), 2% Zn. (zinc). After each process bath, the wire passes through an intermediate clean water bath.

After the final water bath has removed any traces of the plating solution the wire passes through a dryer to remove any surface moisture. (The plating process does not completely cover the surface of the wire but leaves microscopic pores within the plating. Any external moisture may react with the exposed steel surface leading too rust formation). The wire is then coated with a resin solution which protects the wire and helps in the bonding process with the tyre manufacturers rubber compound when the wire is formed into tyre beads. Finally the wire is wound back onto 450 kg customer's reels through a take-up winding machine via a set of straightening rollers.

4.6 Straightening Rollers

Straightening rollers are used in the final quality control of the wire. They cause multiple bending in the vertical and horizontal planes to eliminate any cast within the wire and reducing the axial twist that may be present in the wire after processing, (see figure 9).

The straightening roller block consists of a cast iron or steel frame on which are mounted two roller carriers, one fixed and the other free. The bottom roller carrier is firmly secured to the block by three screws and the upper carrier retained by two screws which allow it to be adjusted vertically. Each carrier has 7 straightening rollers secured by shoulder bolts which allow them to rotate freely.

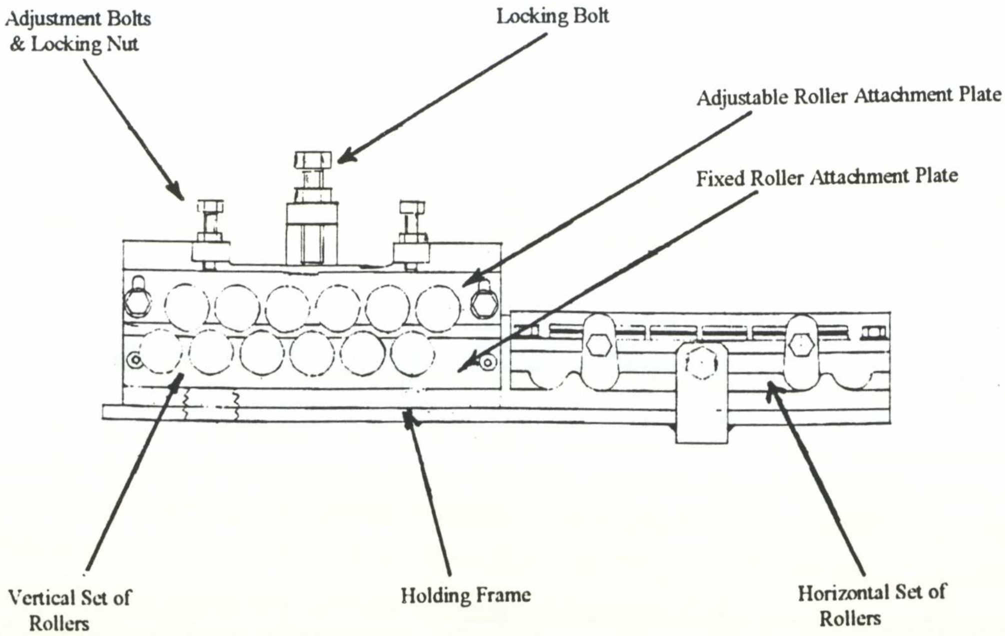

Figure 9 : An illustration of a set of horizontal and vertical straightening roller blocks.

Once the wire has been threaded through the blocks, wire straightening adjustment is carried out by the means of the bolts on each of the blocks. By tightening the bolts, a load is applied to the wire, through the rollers, which, by a process of bending and reverse bending in the vertical and horizontal planes, straightens the wire. Adjustment of the bolts affects the wire in a different way: the first bolt, as the wire enters the rollers, predominately affects the axial twist within the wire where as the second bolt affects the straightness of the wire.

4.7 Discussion

The process of wire reduction is not complicated, it is the way it is achieved that influences the quality of the wire and the required mechanical properties. At each stage of the process the rod / wire is passed over, through and around pulleys and drawing blocks incurring bending and reverse bending before being finally wound onto a steel reel. The questions raised from reviewing the process were:

- What effect on the wire does the whole process have in relation to axial twist?
- Where to select a starting point for the investigation ?
  - i) at the start of the process, first stage drawing,
  - ii) the middle after patenting or
  - iii) at the end with the final plating of the wire.

Looking at the whole process, it was considered that at each stage, axial twist could be induced into the wire. With each change of direction over pulleys and guides, could the wire be storing axial twist within itself only to be released when it was free from the processing constraints? The possibility is there during the two drawing stages, but during the process the patenting of the wire rod refines the grain structure to become more ductile. Could this stage of the process reduce or eliminate the effect of axial twist that may be induced into the wire rod from the first stage drawing process?

This posses the question 'what is it that could be monitored and measured, to compared against the problem exhibited at the end of the plating process?

Compared to the two drawing stages, patenting the wire is the slowest process, there are areas of free wire to set up monitoring equipment, but this will not show what was happening within the plating process. The wire had still to go through another drawing process, travelling at speeds of up to 1500 m/minute when it is wound onto a 450 kg steel reel and ruled out any kind of investigation of the final drawing process. The only alternative that remains is to follow the trail back from the problem. Start with axial twist, take the measurable parameters e.g. tensile strength, diameter, ovality etc. and try to formulate a pattern or model that could highlight the factors influencing the wire.

The plating process area does not lend itself for setting an investigation and conducting experiments. The condition of the processing equipment e.g. the let-off's and take-up's are covered in soap dust and cumar resin, coupled with a wire speed of 4 m/s, it is difficult to find an area within the process to monitor the wire. The plating process itself, accommodates half of the line and is an environment which is not kind for either engineers or equipment. The current data from the joint beadwire task force has demonstrated that lead bath and wire sinkers do not a significant roll in the inducement of axial twist.

The correction of axial twist is through the straightening rollers, monitoring of the wire would be possible but the question is, what ever is measured can this be correlated with the measurements of axial twist? The wire itself has not been investigated fully, axial twist is induced Torque, which is captured by the wire? Could this be the key to the problem and through basic first principles, can an explanation be found and a theoretical model formulated? All these questions are investigated and developed in the following chapters.

Throughout the tyre bead wire reduction and plating process, axial twist could be due to the result of three elements within the process; the manufacturing process & its variability, the actual wire itself and its material & dimensional variations. If it is found that it is the variation in the manufacturing process, the problem can be overcome by identifying the area of the process and making it more consistent. If it is found to be connected with the wire dimensions then this will be machine related and if it is found that it is variation within the material itself then the metallurgy of the process will have to be better controlled.

Chapter 5

Significant Parameters Affecting Twist

5.1 Background

When considering axial twist, the first immediate question which arises is where to start the investigation and how? In the factory environment, practically the only present approach to obtain a measure of axial twist is after each reel is plated, pulling a sample length of wire from the reel, freeing the end which has been bent at right angles and watching it rotate. The amount of rotation observed is very subjective and calculated in quarters of a rotation, which restricts any type of real time monitoring of the problem.

Using brainstorming methods, several contact (marking the wire with a thin white line) and non contact (vision system) measurement solutions were put forward as possible ways to measure axial twist in the wire under process conditions. However as the wire travels at over 266 m / minute (800 ft / minute) and the wire diameter being studied is less than 1.0 mm, it was considered to be impossible to obtain any useful on-line, real time measurement of axial twist. With this in mind, the only logical place to begin the investigation was at the end of the plating line where axial twist is currently measured and to work backwards down the process.

5.2.1 Building a Model

A variety of mechanical and physical process parameters were being measured after the wire was plated, as part of the companies quality control procedures, before despatching the reels of wire to the tyre manufacturers. Since it is not possible to test the wire as it is processed, a method to build up a suitable picture of the plating process which incorporates the known physical and mechanical properties was required. After research in to the design of experiments, the Taguchi modelling technique was found to be the most suitable method.

5.2.2 Taguchi Modelling Technique

Dr G. Taguchi was in charge of research and development for the Electrical Communication Laboratories for Nippon Telegraph and Telephone company. He was responsible for the productivity within the department and in order to improve the cost and efficiency of experimentation, developed an approach for the design of experimentation. His approach is technological based rather than statistical rigour and has been acclaimed for its completeness and ease of use. The concept is based on the relationship between variation of the factors being investigated.

Taguchi modelling method is an off-line Quality Engineering approach which complements on-line quality control systems such as SPC. The methodology encompasses a range of techniques for experimental design, which are applicable to most areas of product design and manufacture. Traditional quality control relies on a combination of in-process inspection and statistical methods employing control charts. These techniques are used to tightly control manufacturing process. However, such approaches become strained as products become more complex. Taguchi modelling minimises the number of changes required to each variable when searching for possible combinations of factors. Standard factorial tables are used which replace traditional one variable at a time experiments. This minimises the effort and finds the performance plateau which avoids sensitivity of performance to small changes in variables.

5.2.3 Beadwire Process Model

To enable a picture of the process influences to be established on the wire as it passes through the plating process, its effects on material & physical properties and hence determine any relationship with axial twist, a series of wire samples were taken. Samples of straight wire were obtained from two ends, off plater number two, producing 0.965 mm diameter beadwire.

The physical properties of the wire samples tested were as follows;

Ultimate Tensile Stress (UTS) (MN/m^2),

0.2% Proof Stress (%),

Breakload (N),

Elongation (%),

Torsion to Failure (No of Turns to Failure),

Residual Stress (R),

Diameter (mm).

- A computerised tensile testing machine was used to obtain; Ultimate Tensile Stress (UTS), 0.2% Proof Stress (%), Breakload (N) & Elongation (%) results from each sample taken.
- Torsion to failure is obtained by clamping the specimens between two sets of jaws 200 mm apart and rotating one end until the sample broke.

- Residual Stress within the wire surface is found by measuring the change of position of a wire sample after dissolving part of the wire away in acid. A 100 mm sample length of wire is laid out on a piece of paper and its ends recorded. Placing on a section of the outside diameter a protective coating (nail varnish) along the whole length of the wire, the sample is dissolved in nitric acid over a given time period and then re-measured noting the change of position of the sample against the original recorded on the paper. The difference in readings gives the amount of residual stress in the wire sample surface.

The data from the samples is then tabulated against the response variable, axial twist (measured when the samples were taken) and the mean value for each variable established (see appendix 1). A mean point is established for each set of variables, the higher values were classed as positive (+ve) and the lower values classed as negative (-ve). This is carried out to enable the data to be back fitted into a model array.

A combinations of the physical and mechanical properties are selected in accordance with the Taguchi experimental design set up. Corresponding values are then fitted back into a Taguchi array, either using a 8 by 8 or 16 by 16 array, depending on the number of fitting samples, the data entered into a basic computer program and the resulting deviations influencing axial twist recorded. The matrixes represents a known factor or a combination of factors which may effect the process and influence axial twist. The results, sum of squares are tabulated, highest first and the values are plotted on a simple (X,Y) graph to form a scree diagram and it is from these graphs the most significant values or factors are determined in relation to axial twist, the higher of the deviation calculated the greater the influence.

Set 4 Scree Diagram

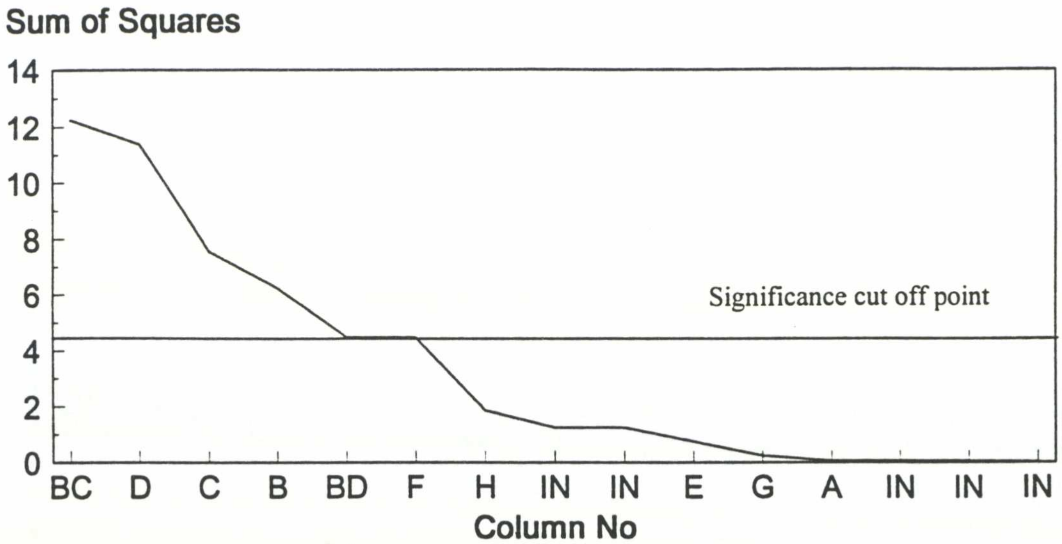

Figure 10 : Scree diagram - Results from set 4 of back fitted data, highlighting the factors that deviate from zero within the process that influence axial twist. (A = Ultimate Tensile Stress, B = Elongation, C = Torsion to Failure, D = Residual Stress, E, F, G, H and IN are minor interactions)

The scree diagram in figure 10 shows the results from set 4 of back fitted data. The resulting calculated 'deviation from zero of axial twist' shows that a combination of factors, elongation & torsion have the greater influence than each of the single factors. The next significant factors are residual stress, torsion and elongation respectively with the fifth being a combination of elongation & residual stress. The line that passes through the graph at 4.5 (sum of squares) is set after reviewing the completed graph and is a cut off point for all factors or combinations of (falling below the line) which are considered not to be significant and affect the axial twist.

5.3 Beadwire Model Analysis

Taguchi Modelling is a technique for the determination of relationships between various factors and a known variable within a system. Back fitting the data into the model array may not be classed as an approved approach but as a technique for analysing a number of known variables within a system with corresponding data, it is believed to be valid[11]. It also served as a basis for further study.

The results from the five sets of data have highlighted that as axial twist deviates from zero it seemed to increase with greater ductility. This suggests that variations in stress relief (i.e. the lead bath) were significant in influencing the physical properties produced by the finish drawing operation. Similarly, at the final stage of the process, it was hypothesised that the straightening rollers, working the wire, could be increasing the axial twist effect. In particular the rollers may be over working the wire, due to changes in ductility, combined with variation within the roller blocks exacerbated by general tolerances, wear and lack of operational maintenance.

Absolute variation suggested that axial twist was increased inversely with diameter and torsion. This pointed to an influence from the straightening rollers with a change in diameter, 'wire ovality', which may effect the amount of force applied to the wire by the rollers, so giving rise to changes in axial twist within a reel. The general conclusion drawn at this stage, based on the Taguchi experimental evidence, suggests that the actual phenomenon is ***Elastic*** in nature rather than a ***Plastic*** deformation problem.

5.4.1 Line Wire Samples

To assist in the analysis of axial twist origin and to determining the actual effects of the process on the wire as it passes down the plating line, line samples i.e. from the let-off's (uncoiler) to the take-ups (coiler), were taken from a number of wire ends from Plater 2.

To simplify the analysis, the line was split into 7 areas (as represented in figure 11). Each sample of wire is secured at both ends of each section, the leading end of wire is cut and that sample tested for axial twist. The sample is then removed, analysed for straightness and cut into sample lengths ready for testing for the wires mechanical properties. The properties of each of the wire samples tested were; Ultimate Tensile Stress (UTS), 0.2% Proof Stress, Breakload, Elongation, Torsion to Failure, Residual Stress, Diameter and Ovality.

The data obtained from each sample are tabulated for each wire sample end (see appendix 2). Sample 8, was wire taken as it had just been straightened and sample 9, wire taken from the completed reel.

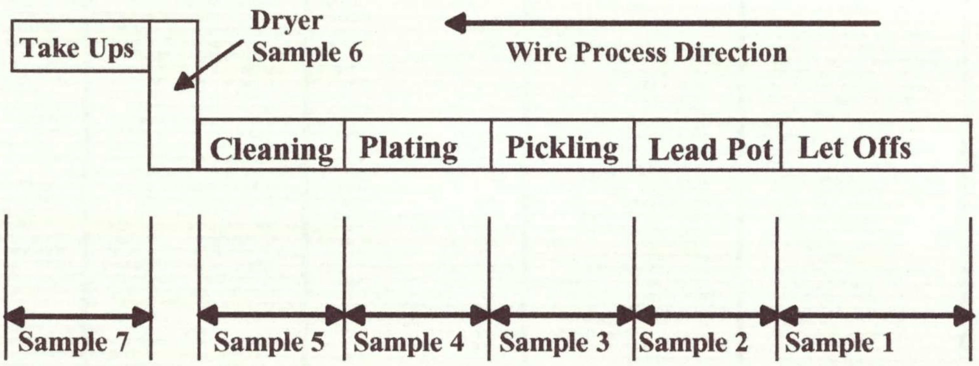

Figure 11 : Pictorial Representation of 'Plater 2' line wire sampling.

The limiting factors with this exercise is that the wire does not come to a dead stop on the line when the take-up end is stopped and that the wire in several sections i.e. lead pot, plating tank and dryer, logistically can not be removed immediately after the wire has come to rest, so succumbing to greater periods of heat than when being processed. This ultimately caused some results from each line tested to be lost due to the wire samples being over heated in the lead pot and corrode within the plating tanks before being removed. These missing results are marked with a (- or **C**) in the results.

5.4.2 Line Sample Results

The restricting factor of the wire not coming to a dead stop on the line in several sections when the wire was not removed immediately where found not to have an effect on the overall results from the respective sample areas.

In analysing each section of the second plating line, the wire straightness was found to followed the shape of specific section / areas the wire sample was taken from (i.e. lead pot guide rollers and sinkers and dryer dog leg configuration) but the middle sections were generally straight with hooked ends where the wire had been pulled over the wire guides and bath wears. The amount of axial twist found in each section was high, with a twist of > +/- 1 turn and as expected reduced after passing through the straightening rollers.

5.5.1 Evaluation of Customer Beads

The problem of axial twist within the wire ultimately affects the tyre manufactures and an analysis of both good & bad beads from several customers was conducted.

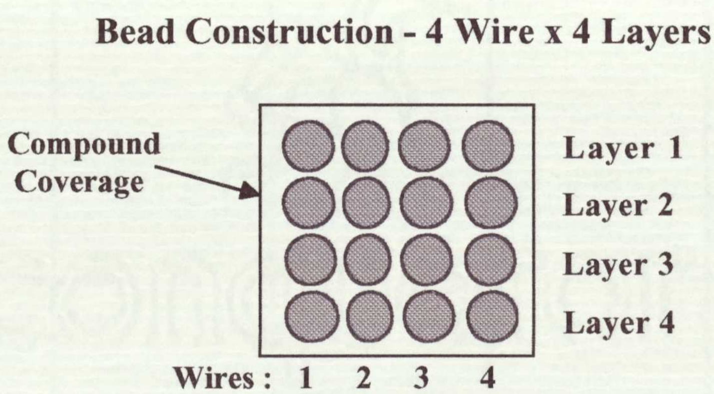

Figure 12 : An illustration of a section of a typical tyre bead tape construction.

Within the production of a 'bead' for a tyre, the ends of a number of reels of wire are brought together, called a 'catenary' [1]. The wire is pulled over heating elements to raise its temperature so that the rubber compound will bond more easily, then pulled through a die set within a extruder machine which deposits a thin layer of rubber compound to form a tape of wire and rubber which is finally cast over a set of grooved rollers before being wound onto a former to produce a tyre bead.

Basis of Investigation :

- To examine both good and rejected bead samples from different tyre manufacturers.
- To determine cast variability within the bead each wire from convolution to convolution.
- Note compound coverage of each bead formation.
- To determine the flatness and helix of the wire.
- Variations in the bead forming machines

Dissection of the wires from the bead construction is carried out using a Stanley knife to cut through the compound before each wire segment is cut from the bead. The analysis was conducted by removing each tape layer from the bead, in the reversed order as it is formed on the winder, then dissecting each cross section of wire, starting from left hand wire.

The following definitions are used to aid the dissection analysis (see figure 13) :

- The 'cast' within a wire is the inner diameter 'D' which is formed when the wire is in a free state and not bound by any constraints.

- The 'helix' within the wire is the distance between each end of the sample when pivoted at the central point 'd1'.
- The 'flatness' of the wire sample is the max. height of one end of the wire sample when placed on a flat surface 'd2'.

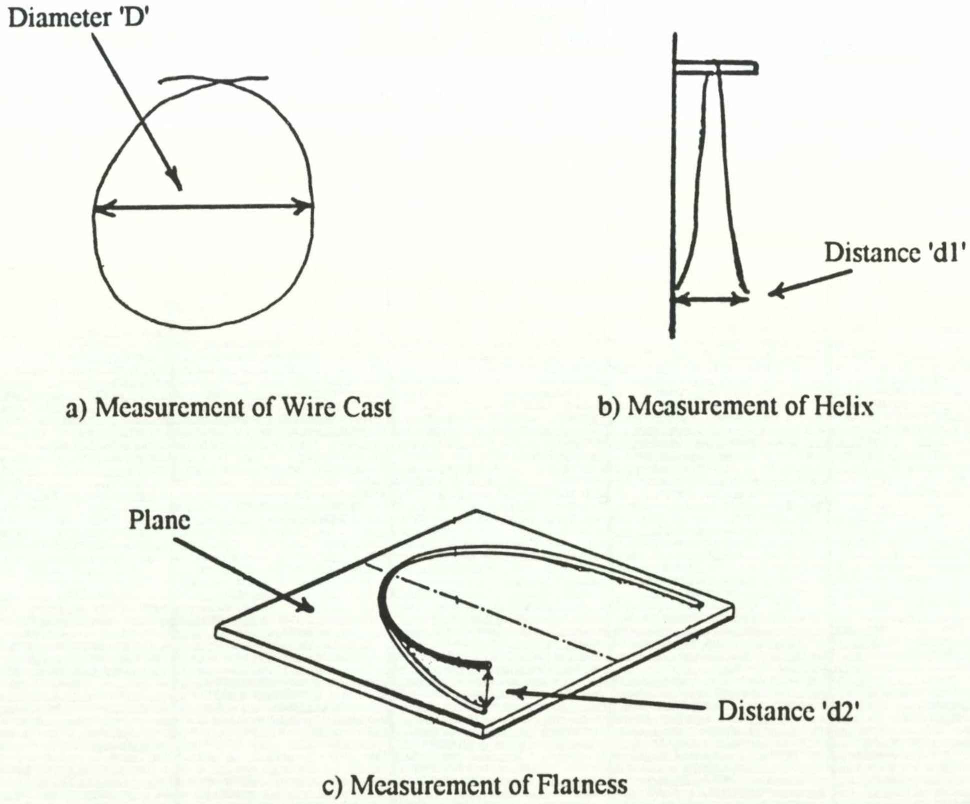

Figure 13 : Illustrations of the measurement and evaluation methods of dissected customer tyre beadwire.

5.5.2 Customer Beads - Dissection Findings

a) Cast : This varied throughout the bead construction, between each layer of tape & wire and between samples from the same tyre manufacturer. Cast of some of the wire in several layers of each bead was found to be elliptical and measure between 254 & 414 mm in diameter. The size of cast varied throughout the bead but the cast of the wires in each layer of tape were similar.

b) Compound : Coverage on the wires varied between manufacturers, the make up of compound and found that the coverage to be either be uniform over each of the wire within the tape construction, which was generally smooth & tacky to the touch or poor around the bead tape edge where the wires had bunched closer together whilst the bead tape was being formed. The compound on these wire was found to be dryer with a rough surface texture.

When dissecting the wires from each tape layer the compound was found to peeled away from some of the leading ends of each wire leaving it bare and this was possibly due to the tackiness of the compound or the thinness of the coverage on the wires.

c) Flatness : All the wires varied in flatness, the cut wire ends were found to vary from 5 to 130 mm, standing proud from a flat surface. The rejected beads were found to exhibit the greater amounts of variation in flatness.

*d) Heli*x : This varied throughout the bead layers and throughout a single wire. Variation was found between 48 & 312 mm.

5.6 Discussion

The physical and mechanical properties are an important set of factors that have to be considered and analysed and as these results could only be obtained after the plating process has been completed. Taguchi 'design of experiments' provided the answer to how to analyse data after the fact. We know the response variable connected to the measured factors, so if the process is reversed then possibly when the coefficients were calculated, the resultant inter-reactions will highlight something significant, a factor or combination of factors that can further the investigation.

Some of the inter-reactions of the factors measured highlighted the variation in stress relieving of the wire through the lead bath, which influenced the physical properties produced by the finish drawing operation. This was an inter-reaction that was known about, highlighting the increase in ductility (elongation) and a reduction in tensile & yield strength after passing through the lead bath (see table 2). This demonstrated that data we had, had validity and that any conclusions gained would be pointing the investigation in the right direction.

The results highlighted that after the wire has been stress relieved, the increased in ductility of the wire possibly plays a major role in the inducement of axial twist. Could the amount of twist induced be related to the amount of ductility and could a relationship be measured and correlated? Through simple torsion theory, a torque applied to the wire will induce a twist and 'Modulus of Rigidity' as part of the equation to determine the amount of torque applied could be measured within the wire. Could any change in the modulus of rigidity of a wire sample be correlated against a measured value of axial twist? This may be a significant factor in understanding axial twist and its inducement within the plating process. If a correlation can be established then the amount of twist (torque) being applied to the wire can be calculated and give an indication as to where within the process twist is occurring. An investigation into the measurement of 'modulus of rigidity' of the wire is discussed in chapter 6.

The influence of the straightening rollers produced some different results than expected. The rollers are set to work the wire and reduce axial twist and it had not been considered that the rollers could also be inducing twist by over or under working the wire as it passed through the two roller blocks. The general condition of the roller blocks and the poor operational maintenance of the take-up end were factors which was not investigated at this time but could effect the amount of axial twist within the wire. Further suggested influence from the straightening rollers, found the possibility that a change in diameter, ovality of the wire, may effect the amount of force being applied through the straightening rollers thus giving rise to changes in axial twist. The small amounts of ovality recorded suggested that this was misleading and could be discounted.

The positive inter-reactions of the results hinted that rather than looking at the mechanical aspect of the process, further investigation should be conducted on areas where the wire direction is changed, the wire being pulled over or around pulleys and through wire guides. The results suggested that it was more of an influence that effected the wire and induced axial twist.

The line samples from plater two were taken to gain an understanding of the affect on the wire by the process, due to the difficulty in monitoring parts of the plater which contained cleaning and plating chemicals. The exercise enabled the amount of axial twist, exhibited by the wire within the process to be measured and an understanding gained of the physical influences on the wire i.e. pulleys and wire guides. The sample results (see appendix 2) highlighted the effect of the wire being pulled or passing over pulleys and guides, but the effect was found to be localised at the ends of each sample where the samples were cut from the plating line. This may have been caused during the slowing down of the process before coming to a stop and could be discounted. The amount of axial twist within each sample was found to vary in amount & direction and there was no set pattern found in any of the samples from the wire ends . Some of the degree in twist variation found can be accounted for, as there would be variation in axial twist with the bright wire as it is pulled down the plating process.

The dissection of the bead samples from the tyre manufacturers, was an exercise to see if there was anything within the bead making process that could be correlated to axial twist. The hardest part of the exercise was dissecting each individual wire out of the rubber compound from the bead ring. The general conclusion gain was that part of the tyre manufacturers problems, stemmed from the compound coverage of the wires. If the compound was evenly spread over the wires and that the wires were evenly distributed, then the bead would stay uniformly round. Where the compound coverage varied then there could be instances where high axial twist which could force a bead to kink into a figure of eight shape or allow the end of one of the wires to brake away. For each of the samples investigated, there were no positive correlation that could gained.

Chapter 6

Relationship of Modulus of Rigidity to Axial Twist

6.1 Periodic Frequency

The Taguchi model conducted on the physical parameters of the beadwire after processing highlighted the factors that influenced or interacted to produce axial twist. This did not explain the actual mechanics by which axial twist is induced into the wire. A review of the results from the wire samples highlighted a possible link with axial twist and the steel wire 'Modulus of Rigidity' and this could be developed to form a mathematical model through simple Torsion Theory [11].

$$\frac{T}{J} = \frac{\tau}{R} = \frac{G\theta}{L} \qquad (1)$$

Where :

T is the applied external torque, constant over length L;

J is the polar second moment of area of wire cross section;

R is the outside radius of the wire;

τ is the shear stress at radius R;

G is the modulus of rigidity (shear modulus);

θ is the angle of twist in radians on a length L.

Transposing the equation for θ gives $$\theta = \frac{TL}{JG} \qquad (2)$$

For changes in θ then $d\theta$ this gives an equation

$$d\theta = \frac{\partial\theta}{\partial T}dT + \frac{\partial\theta}{\partial G}dG + \frac{\partial\theta}{\partial J}dJ + \frac{\partial\theta}{\partial L}dL \tag{3}$$

Sample length is standard 10 m there for dL = 0

With $J = \frac{\pi r^4}{2}$ so $dJ = 2\pi r^3\, dr$ (4)

This gives
$$d\theta = \frac{2L}{\pi r^4 G}dT - \frac{2TL}{\pi r^4 G^2}dG - \frac{8TL}{\pi r^5 G}dr \tag{5}$$

$$d\theta = \frac{2L}{\pi r^4 G}\left[dT - \frac{T}{G}dG - \frac{4T}{r}dr\right] \tag{6}$$

6.2 Wire Frequency Experiment

The initial concept of testing the wire to establish its frequency with varying axial twist is simple. Changes in wire material's modulus of rigidity can be correlated with changes in wire periodic frequency. The wire sample [length (L) = 300 mm] is suspended at one end, a weight with a monitoring device is attached to the other and the wire is then gently excited with the oscillations being recorded over a period of time. In practice this proved difficult to set up and required a high degree of accuracy to obtain consistent and meaningful results.

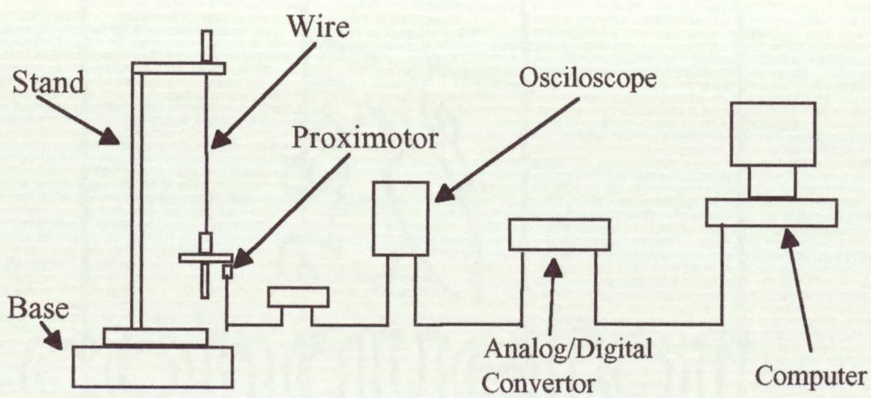

Figure 14 : Illustration of the periodic frequency test set-up.

The initial test set up comprised of a retort stand, a cross beam and a clamp block at the end of the beam to suspend the wire. A 50 mm square aluminium plate and balance weight are attached to a small drill chuck which is attached to the bottom of the wire sample. The wire is then suspended by the clamp, positioning a hole in the plate over a proximotor sensor. The wire sample is slightly twisted axially and released (oscillating the aluminium plate in the horizontal plain) and the oscillating movement of the hole over the proximotor is recorded onto a computer using Matlab Data Logger, recording 50 readings per second over 180 seconds (see table 3).

A initial 12 wires sample were selected comprising of :

Batch No	***Axial Twist***	***Test No***	***Frequency* (Hz)**
18853B	0	T1	2.89
18978A	0	T2	2.9236
21019C	0	T3	2.9419
21015A	1/4c	T4	2.9114
20754A	1/4a	T5	0.2441
21031B	1/4c	T6	2.9175
20755C	1/4a	T7	2.8687
20002C	1/2a	T8	6.4026
20074D	1/2c	T9	2.9114
20753A	1/2c	T10	2.8809
18993C	3/4a	T11	2.8748
18964A	1a	T12	2.8748

Table 3 : Initial periodic frequency test results.
(a - anticlockwise and c - clockwise axial twist rotation).

Problems in oscillating the wire were discovered from the initial results. It was found that when the wire is axially excited, oscillations were induced into the weight, producing a pendulum motion, and a vibration was induced into the aluminium plate. Analysing the original design for the frequency tests, it was found that the problem, of inducing unwanted oscillations, was in the rigidity of the retort stand and cross beam. These were replaced by a construction of 10 mm steel plate which allowed a direct method of oscillations the wire axial. This was achieved by attaching the wire by a grub screw into a threaded bar which was positioned into a through hole in the steel plate of the cross beam.

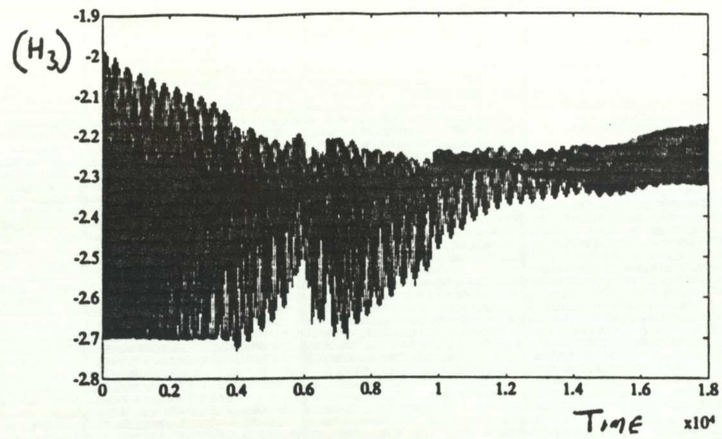

Figure 15 : Example of horizontal vibration Induced into the pick up plate

Testing this new frame it was found that a frequency variation occurred if the wire, drill chuck, plate and weight were not allowed to come a complete rest before each test oscillation. With only a small variation within the initial samples and large discrepancies occurring within the initial test, a repeatability test was carried out on a proportion of wire sample (see table 4).

For the repeatability test, each samples (T1 to T7), were set up in precisely the same way, allowing the wire to come to rest over a period of 5 to 10 minutes. The wire was then excited by turning the screw within the plate by a quarter of a turn, which induced axial oscillation within the wire. The results from the 7 samples proved that a consistent frequency could be obtained over a series repeated tests and by allowing each wire set-up to come to a complete rest, produced a repeatability in frequency results of 99.79%.

Test No	*Batch No*	*Axial Twist*	*New Frame (Hz)*	*Repeat Test R1 (Hz)*	*Repeat Test R2 (Hz)*	*Repeat Test R3 (Hz)*	*Repeat Test R4 (Hz)*
T1	18853B	0	3.4851	2.8870	2.8870	2.8870	2.8870
T2	18978A	0	2.9236	2.9236	2.9236	2.9236	2.9236
T3	21019C	0	0.2441	2.9419	2.9419	2.9419	2.9419
T4	21015A	1/4c	2.9175	2.9114	2.9114	2.9114	2.9114
T5	20754A	1/4a	2.8137	2.8137	2.8137	2.8137	2.8137
T6	21031B	1/4c	2.9114	2.9236	2.9236	2.9236	2.9236
T7	20755C	1/4a	2.8748	2.8687	2.8748	2.8748	2.8748

Table 4 : Frequency repeatability test results.

Test No	*Batch No*	*Axial Twist*	*Frequency Test (Hz)*	*Test No*	*Batch No*	*Axial Twist*	*Frequency Test (Hz)*
T8	20002C	1/2a	2.9053	T15	18911A	1/4c	2.9175
T9	20074D	1/2c	2.9114	T16	18944A	1/2c	2.8503
T10	20753A	1/2c	2.8809	T17	18932B	0	2.8687
T11	18993C	3/4a	2.8687	T18	18472D	0	2.8748
T12	18964A	1a	2.8748	T19	18932D	1/2c	2.8809
T13	18929A	1/4c	2.8381	T20	18409C	1/2c	2.9236
T14	18911B	1/4c	2.9236	T21	18932A	1/2c	2.8748

Table 5 : Continuation of wire frequency test results

Matlab software was used to collect and analyse the frequencies produced by the test, which recorded onto a 486 micro computer, through an Analog/Digital converter and a small macro, in basic programming language was produced to automate the process.

Macro in basic language :

```
b1d = input ('Enter the name of the variable :  ');
nsamp = 2^13
b2d = b1d(1:nsamp)
fftb2d = fft(b2d);
plot(imag(fftb2d(100:nsamp/2)))
[a,b] = max(abs(fftb2d(100:nsamp/2)))
Total_Time = nsamp*20e-3
Freq = b/Total_Time
plot(abs(fftb2d(100:nsamp/2)))
```

6.3 Frequency Analysis

Correlating axial twist with the resulting frequencies (tables 4 & 5), the wire samples produced a reading of 0.3731 and showed that there was no overall match between axial twist and the wire's modulus of rigidity.

Recalculating for regression of results using a basic computer programme to analysis the data to 15 possible curves, gave a best possible fit of 0.3097 for axial twist deviation from zero and 0.1323 for actual axial twist.

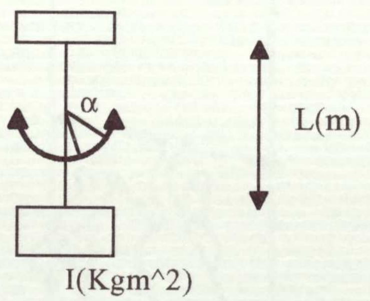

Figure 16 : Diagram of a suspended wire sample.

L = Length of wire, I = Suspended Mass, α = Angle of Twist

There are a number of elements that can effect the amount of twist in the wire, torque applied, radius and modulus of rigidity and that the level of each effect by each element on the wire depends on their proportions. To identify variations in Rigidity Modulus and the influence of radius, periodic frequency test results were analysed by taking Simple Torsion theory (equation 1) and transposing the equations through Laplace transforms to find the change in natural frequency due to a change in Rigidity Modulus and or a change in radius;

Total Torque, $$T = \frac{\theta JG}{L} + I\frac{d^2\theta}{dt^2} \qquad (7)$$

Where J = Second polar moments of area of the wire (= $\frac{\pi r^4}{2}$).

G = Modulus of rigidity of wire material.

L = Length of wire.

I = Polar moment of inertia of the suspended mass.

θ = Angle of twist.

In Laplace domain (assuming zero initial condition)

$$\bar{T} = \theta\frac{JG}{L} + IS^2\bar{\theta} \qquad (8)$$

Refining $\frac{JG}{L}$ as torsional stiffness 'K'

$$\bar{T} = \bar{\theta}[IS^2 + K] \qquad (9)$$

Therefore $$\bar{\theta} = \frac{\bar{T}}{IS^2 + K} \qquad (10)$$

$IS^2 + K$ factors as $$I^2\left[\left(S + \frac{\sqrt{K}}{I}\right)\left(S - \frac{\sqrt{K}}{I}\right)\right] \qquad (11)$$

and so the natural frequencie (or eigen values) of the system are

$$W = \pm\sqrt{\frac{K}{I}} \tag{12}$$

Taking the modulus value of W :

$$|W| = \left(\frac{K}{I}\right)^{\frac{1}{2}} = \left(\frac{JG}{LI}\right)^{\frac{1}{2}} = \left(\frac{\pi r^4 G}{2LI}\right)^{\frac{1}{2}} \tag{13}$$

This can be writen as :

$$|W| = r^2 G^{\frac{1}{2}} C\ , \quad \text{where} \quad C \equiv \left(\frac{\pi}{2LI}\right)^{\frac{1}{2}} \tag{14}$$

thus

$$\frac{\partial |W|}{\partial r} = 2rG^{\frac{1}{2}}C \quad \text{and} \quad \frac{\partial |W|}{\partial G} = \tfrac{1}{2}r^2 G^{-\frac{1}{2}}C \tag{15}$$

$$\partial |W| = 2rG^{\frac{1}{2}}C\partial r + \frac{1}{2}\frac{r^2 C}{G^{\frac{1}{2}}}\partial G \tag{16}$$

The frequency test results from the wire samples did not correlate with the axial twist readings and varied with samples exhibiting the same degree axial twist. It can be deduced that variation in 'Modulus of Rigidity' for small diameter wire has an insignificant affect with regards to axial twist and can be classed as a constant.

The Taguchi model of the physical parameters (discussed in the previous chapter) also highlighted the variations in diameter did not affect the wire, so, for the purpose of the theoretical calculations, dr, can be classed as zero. From equation 16 the 'Modulus of Rigidity' is thus calculated at 9.5 x 10^{10} Pa and from equation 6, a theoretical value for the change in the angle of twist can be determined.

6.4 Theoretical Calculation of Axial Twist

To calculate a value for theoretical axial twist it is required to look at the mechanism of twist being applied to the wire.

Twist: **Torque** = **Force Δr**

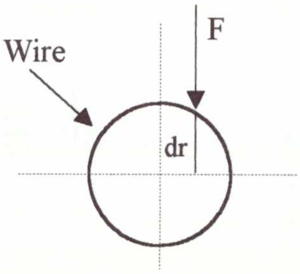

Figure 17 : Pictorial Representation of a force, F, being applied to a cross section of wire

The force applied to the wire at a distance dr, will produce a Torque i.e. induce twist within the wire. To understand the nature of axial twist, a theoretical value of torque, to twist the wire by one revolution, 2π, was calculated.

From equation 6, total torque can be calculated from

$$\text{Total Torque} = \frac{JG\theta}{L}$$

Where L = 3 m, G= 9.5×10^{10} Pa, $\theta = 2\pi$ and

$$J = \frac{\pi r^4}{2} = \frac{\pi(10^{-3})^4}{2} = 1.57 \times 10^{-12}$$

Therefore T = 1.57×10^{-12} X 9.5×10^{10} X $2\pi/3$ = **0.31 Nm**

Torque (T) over sample length of 9 m = **0.104 Nm**

Transposing the known values into equation 6, where :

r = 4.825×10^{-4} mm	Radius of wire,
dr = 0 mm	Ovality of the wire radius,
l = 9 m	Length of wire sample,
G = 9.5×10^{10} Pa	Modulus of Rigidity,
dG = 0 Pa	Change in Modulus of Rigidity,
T = 0.104 Nm	Torque,
dT = 50%	Change in Torque,
θ = To Find	Twist within the wire.

With dG and dr equal to zero then

$$\frac{T}{G}dG = 0 \qquad \text{and} \qquad \frac{4T}{r}dr = 0$$

Therefore $\quad d\theta = 1112.8 \times [\ 0.05 - 0 - 0\ ]$

$\quad$ **dθ = <u>55.64</u>** Degrees

The amount of torque required to twist a 9 m length of wire is very small at 0.104 Nm but theoretical calculation shows that a change in torque by 50% produces a twist of 56 degrees and the magnitude in torque within the process is thus four fold.

6.5 Orthogonal Array

An orthogonal array is an experimental design constructed to allow a mathematical independent assessment of the effect of each of the factors being investigated. Factors are assigned to columns and each row indicates a combination of factor levels.

In an orthogonal experimental design, it is the average change in response over a number of experimental changes not the outcome of just one experimental set. This allows the comparison of factor levels under different experimental conditions which also increases the assurance of reproducibility. The arrays used are one form of fractional factorial design, conducting fewer experimental runs and allow the same amount of effective information / data that could be gained from using a full factorial design.

An important feature for evaluating factor levels is when they change orthogonally, other effects are not mixed in. When evaluating the experimentation data, comparisons can be safely made under various conditions within the experiment, rather than holding onto a fixed condition. The reliability and of the experimental effects is the greatest benefit to

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be derived from using orthogonal arrays. A variable with a constant effect under various conditions is able to be reproduced, despite variations in manufacturing conditions.

A proof of the statistics behind the analysis can be shown through the theoretical background of the Taguchi experimentation, orthogonal array :

Q represents the response variable axial twist and is a function of torque (T), radius (r) and modulus of rigidity (G):

$$Q \to F(T, r, G) \quad (17)$$

A small change in any of the functions (T,r,G) will produce a change in axial twist, dQ, thus:

$$\Delta Q \to f(T, r, G) \to f(T, \Delta T, r, \Delta r, G, \Delta G) \quad (18)$$

$$\dot{Q} = \Delta Q \quad (19)$$

The matrix of equation 23 becomes :

$$\begin{bmatrix} \dot{T} \\ \dot{r} \\ \dot{G} \end{bmatrix} = [\Delta] \begin{bmatrix} T \\ r \\ G \end{bmatrix} \quad (20)$$

$$\delta Q = \tfrac{\vartheta F}{\delta T}(T, r, G).\delta T + \tfrac{\delta F}{\delta r}(T, r, G).\delta r + \tfrac{\delta F}{\delta G}(T, r, G).\delta G \quad (21)$$

$$\left[\dot{Q}\right] = [J*]\left[\delta\dot{T}, \delta\dot{r}, \delta\dot{G}\right] \quad (22)$$

Where J* is the Jacobean Statiory Matrix[13] becomes

$$\begin{bmatrix} T \\ r \\ G \end{bmatrix} = \begin{bmatrix} j_{11}, j_{12}, j_{13} \\ j_{21}, j_{22}, j_{23} \\ j_{31}, j_{32}, j_{33} \end{bmatrix} \begin{bmatrix} \Delta\dot{T} \\ \Delta\dot{r} \\ \Delta\dot{G} \end{bmatrix} \quad (23)$$

Thus in the experimental design through the orthogonal array :

$$\dot{Q}_1 = F_1(T, r, G) \quad (24)$$
$$\dot{Q}_2 = F_2(T, r, G)$$
$$\dot{Q}_3 = F_3(T, r, G)$$

Thus the matrix becomes :

$$\begin{bmatrix} \frac{\delta F_1}{\delta T} \cdot \frac{\delta F_1}{\delta r} \cdot \frac{\delta F_1}{\delta G} \\ \frac{\delta F_2}{\delta T} \cdot \frac{\delta F_2}{\delta r} \cdot \frac{\delta F_2}{\delta G} \\ \frac{\delta F_3}{\delta T} \cdot \frac{\delta F_3}{\delta r} \cdot \frac{\delta F_3}{\delta G} \end{bmatrix} = J \qquad (25)$$

So [J] for $\dot{Q}_1, \dot{Q}_2, \dot{Q}_3 = 0$ (26)

So for each change factors, [J], that produces a response equal to zero thus gives the corresponding values of the factors being measured within the experimental design.

6.6 Discussion

Returning to first principles and using the simple torsion theory has given the first tangible indication of the root cause of axial twist. It could be said that the evidence was in plain sight, as twist is just a storage of torque within the wire. But the process itself has masked the indicators of the problem, reduction of axial twist is by mechanical working through the straightening rollers and the wire passes over surfaces through the plating process which has been presumed to induce axial twist.

The simple torsion equation has made the investigation take a step back and really consider the basic principles of the problem, what are the factors within the axial twist phenomenon? Considering the main components, we have an understanding of torque, which is the main contributing factor with produces the twist and diameter, the finished wire size. The third factor change in the modulus of rigidity of the wire which at this stage was an unknown and the questions posed, could the modulus of rigidity within the wire be measured and what degree of influence does it have within the torsion equations.

The periodic frequency experimentation took a period of time to prepared and over come unwanted vibrations within the aluminium plate, but the resulting frequencies results contributed in discovering a major piece of the jigsaw puzzle. The analysis and correlation of the results against axial twist established that the modulus of rigidity was not a contributory factor and could be classed as a constant within equation 6. Coupled this with the change in diameter, ovality, which was found to be very small, an average 0.002 mm, then the main factor in the inducement of axial twist within the wire is torque.

The calculated theoretical value of torque has shown that there only requires a small amount of force to twist the wire. The plating lines have numerous places where the wire comes into contact with the process i.e. the pulley wheels used on the let-off's and take-up's at each end of the plater. The amount of force exerted on the wire at each point of contact would vary from point to point and the direction of twist would also vary due to the direction of the force applied (see figure 16). Each point of contact could be affecting the wire in either a clockwise or anticlockwise direction and this could be the main influence in causing axial twist. To investigate and calculate all the points of contact would take an extremely long time and would not contribute to the project.

It could be expected then, that axial twist within the wire, when it reached the end of the process would remain constant. The straightening rollers, once adjusted, would produce a near twist free wire throughout a reel of wire. This has not been found in practice, tests carried out taking wire samples from various sections throughout a reel, found large variation in the amount of axial twist and direction. The questions raised from this is, what influences the low levels of induced torque within the process and produces the variation in axial twist throughout a reel? Why do we not see a nominal amount of twist being produced that can be reduced by setting the straightening rollers before each reel is processed?

We can only assume that there is another significant factor that has an influence on the wire and is connected to the inducement of axial twist as the wire plated. These questions are investigated and developed in chapter 7.

Chapter 7

Determining Wire Tension Variation During Manufacture

7.1 Monitoring of the Beadwire

The main problem that had to be overcome in designing an experiment, was how to monitor the wire as it is being processed down the plating line. The only point of control, with regard to axial twist, is through the straightening rollers.

The operator sets up or adjusts the straightening rollers before each reel is processed to produce wire with zero axial twist. This is achieved by applying a load through the two rollers sets, 1 vertical & 1 horizontal, working the wire in each plain to straighten the wire.

The only measurable element within the straightening rollers is the load being applied through the two adjustment pins of each roller set. If a suitable method of monitoring the load being applied, could be set-up, then a practical measurement of the wire processing and the influence of the straightening rollers, could be made.

7.2.1 Straightening Rollers Block Design

Reviewing the design of the straightening roller blocks it was became evident that if an experimental design through the load applied then the type of load monitoring device selected is going to have to be small. This is due to the amount of surface area between each of the pins and upper plate holding the grooved straightening rollers. The existing straightening roller blocks proved to be inadequate for modification, as the majority of the blocks were made out of cast iron, had been made to general specification tolerance and were showing signs of old age. The modified design for the experimental blocks would rest on the type of load cells that could be found to fit into a small space.

The size of the load cells was the main influence in the modified design. The load cells require to be situated centrally under each adjustment pin to enable a accurate load reading to be gained and the overall dimensions of each block be within 0.15 mm tolerance. Each moving part of the blocks has to have a high degree of accuracy as to not induce any error into the experimental trials.

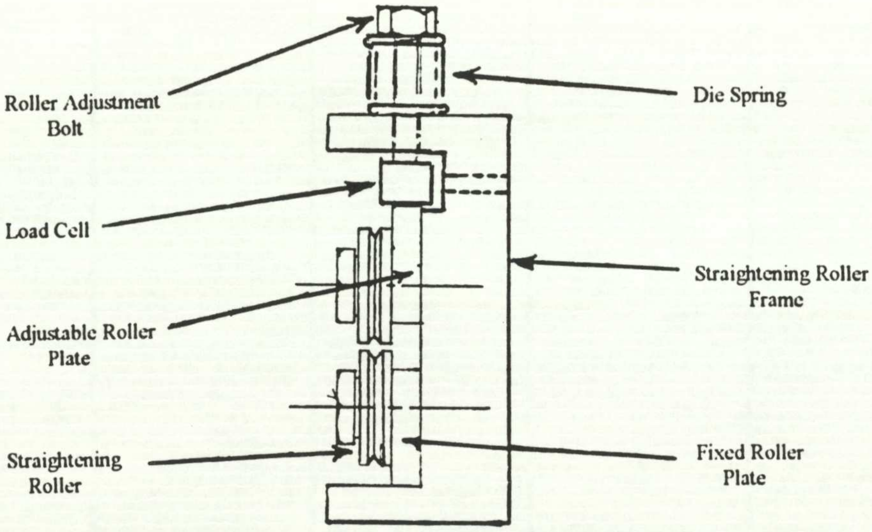


Figure 18 : An illustration of the modification to the design of the straightening rollers to incorporate the load cells.

A modified main block design (x2) was produced by the National Standard's machine shop, using co-ordinated milling and drilling machines. A step had been incorporated to allow the load cells to sit on the adjustable roller plate and a hole drilled through adjacent to each pin to allow the load cell leads to be secured safely away from the rotating rollers. Each set of roller plates had to be accurately machined, drilled and tapped to ensure that each of the 7 roller were equally spaced from its neighbour. To secure the roller onto the plates shoulder screws with a 7 mm ground diameter shoulder were used. To allow for fine adjustment of the bolts, the looking nuts were replaced by heavy duty die springs.

7.2.2 Load Cells

The type of load cell and the maximum load required needed to be determined. A torque meter was used to assess the amount of torque (N) being applied to the 5 mm adjustment bolts on a straightening roller block, producing 0.965 diameter wire and from these results the load applied was calculated. The load being applied through each of the bolts was found to be < 3 KN.

Several manufacturers were found that supplied various sizes and ranges of load cells and the Entran ELH Series Miniature High Accuracy Load Cell (see appendix 3), was selected as the most suitable. The size of the cell is 16 mm in height and 15 mm in diameter which would fit into a standard block without to much modification to the design. The load range of the cell is 5KN max. which gave a margin of safety if any of the cells were to be extended above 3KN when in operation

To operate the load cells a 4 band bridge conditioner and a differential dc pre-amplifier was used. To enable the bridge conditioner to operate within the correct range with a full bridge response, four internal circuit boards had have their Calibration (Rcal1), Zero (Rzero) and Operator (Roperator) resistance modified to enable the cells to operate correctly. A multi-trace monitor was connected to the back of the amplifier unit to collect the readings from the load cells.

7.2.3 Straightening Rollers

To eliminate the possibility of variation from the rollers themselves, that may affect any experimental work, high accuracy straightening rollers were purchased from Whittel Albert, in Germany. The accuracy of the grinding of the V-Groove in the centre of the roller and its position in relation to the wire is factor to be studied. Off setting the force being applied through the rollers, is one of the factors that could ultimately affect the wire.

7.3 Straightening Roller Experimental Model

The Taguchi modelling technique was chosen to assess the settings of the straightening roller blocks in conjunction with the influences of the position of the rollers. A 16x16 array was chosen, with the 4 adjustment bolts and 2 rollers from each block, (rollers 2 & 5 from the adjustable roller plate), being the selected as the parameters within the experiment. To allow for the adjustment of the rollers, washers are placed under each roller, allowing positive and negative movement. Each bolt will be moved by half a turn to produce a significant reaction within the wire. Axial twist is the resultant factor within the experiment and for each segment of the experiment, the process is run for maximum of 5 minutes. This allows the process line to start up and become stable, so that meaningful results can be obtained and ensure that the wire used within the experiment is taken from the same part of the un-plated (bright) wire.

7.4 Load Trace

From each of the sequence of 16 individual experiments a trace, running at 500 mm per hour is obtained of the load applied through each of 4 the load cells (see appendix 5). The results correspond with the results of the Taguchi experiment but significantly, highlight the amount of load variation being experience by the wire as it is pulled down the plating line and through the straightening roller blocks, see figure 19.

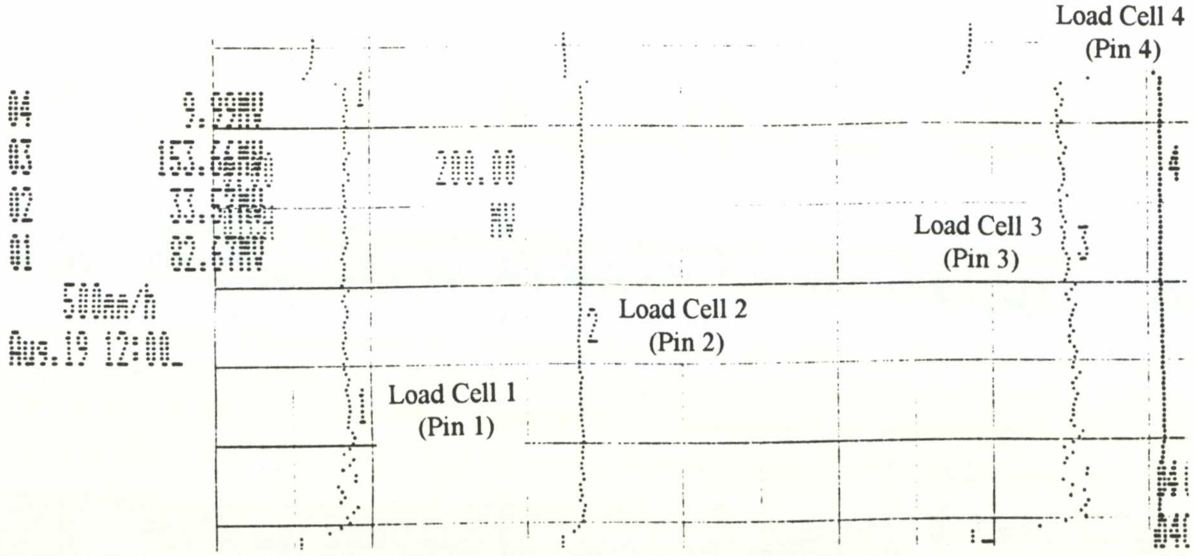


Figure 19 : An example of the trace data readings obtained from the 4 load cells. The output from each load cell is measured in Milli-volts.

Pins 1 & 3 experience the most variation load being applied to the wire were as pins 2 & 4 exhibit only small variations which become more significant when the load variation becomes higher in Pins 1 & 3.

7.5 Straightening Roller Model Results

The indicators from the Taguchi experiment highlighted that then main elements within the experiment are the adjustment bolts. As the load increased individually on pins 2, 4 & 3, the axial twist became worse i.e. moves away from zero and similarly with the interaction between pins 2 & 3. At a low load on pin 3, as the load increased on pin 2, axial twist became worse. For a high load on pin 2 as the load through pin 3 increased axial twist became better i.e. moved towards zero. The load through pin 1 is highlighted as not having a significant effect to influencing axial twist The movement of the rollers in the horizontal and vertical planes is shown not to have any significant effect. There is some inter-reaction between pin 2 and roller 2H but the effect is over shadowed by the reaction of the pins to influence axial twist and therefore was disregarded as a main factor of influence.

7.6 Discussion

Setting up the straightening rollers, incorporating the load cells, gave the investigation its first results that could be directly measured against axial twist. The expectation was that the roller blocks, once set to produce zero axial twist within the wire (refer to chapter 4, section 4.6), would be found to produce a constant load, once the process had reached its operating speed of 4.3 m/s. The results from the loads traces found that after the initial start up, the traces plotted variation in load applied through all 4 pins and highlighted another variation being experienced by the wire.

The variation can only be contributed to one known factor, tension. Tension has been recognised as a possible influence on the wire but as a factor not considered significant and so not included in any further investigations. It was believed that due to the pinning of the wire throughout the process, tension would have a very minor effect and realistically could not be measured, compered and correlated against axial twist. The evidence from the load trace proved otherwise.

The Taguchi model found, that the main contributor to the variation of axial twist during the experimentation was the adjustment of pins one and three followed by pin two (see appendix 4). The increase and decrease in applied load through the adjustment pins corresponded with the changes in axial twist. But we have found from the load trace plotted that there was also a variation in the load being applied throughout the sixteen individual experimental runs. From these conclusions, does this give an explanation of the variation in twist found in the wire?

The answer is yes. It lies with the control of tension within the plating process and is the key to controlling axial twist variation. Twist is induced into the wire by torsion, and captured by the wire. The variation in tension experienced by wire, firstly allows the capture torque to be release backwards or forwards from the many points of inducement. This accounts for some of the variation in axial twist at the end of the process. The amount of twist within the wire also changes when the torsion tries to elasticity free itself, as the tension reduces. So the level of twist entering the straightening rollers varies.

When tension increases the amount of force being applied to the wire at each of the point of contact with the wire also increase. Thus the amount of induced twist will also increase in either a clockwise or anti clockwise direction, depending on the direction of the force being applied.

The tension also effects the load being applied to the wire through the straightening rollers, which alters the setting, so giving rise to the variation in axial twist within the finished reel of plated wire. These three aspects coupled together are the main cause for the variation of axial twist found throughout a reel of plated beadwire. The main control of tension within the process is through the let-off stand. If the above conclusions are to be validated, then tension of the wire within the plating process must be finely controlled. The control of wire tension is investigated and discussed in chapter 8.

Chapter 8

Improvements in Tension Control

8.1 Let-off System

The let-off stands (uncoiler) contain the main control mechanism of tension governs the speed of the wire down the plating process. The take-up (coiler) pulls the bright wire down the plating line from a 450 Kg reel and leaves the let-off stand via 2 V-grooved pulleys before being directed down the plating line via a third pulley, see figure 19.

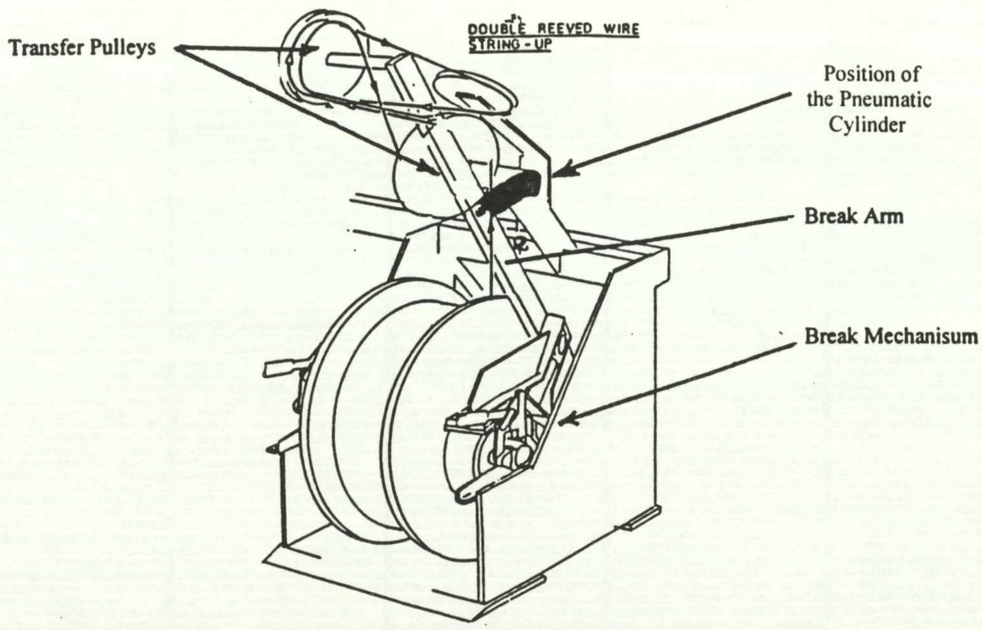


Figure 20 : Illustration of the proposed modification to one of the let-off stand with the new pneumatic breaking system.

The wire tension is maintained through the speed of the reel via a breaking system comprising of a floating arm & return springs on the let-off stand. As the speed wire of the bright wire increases, the quantity of wire between the two pulley wheels expands, allowing the break arm to move outwards and engage the breaking system slowing the reel down. The opposite effect happens as the reel slows down, the quantity of wire between the two pulley wheels reduces, pulling the brake arm away from the break drum, which releases the reel and allows the wire speed to increase. The movement of the brake arm is controlled by a simple spring mechanism.

8.2 Line Tension

Individual readings of wire tension are taken using a hand held tensometer (see table 6) and during the initial stages of the project, selected wire ends on both plating lines were measured twice over an 8 hour shift. The wire tension measurements were taken in the same position on each end, as the wire travels towards the lead bath. The results found that the tension of the wire varied or oscillated as it was being pulled down the plating lines, between 5 and 80 N.

Plater 1				Plater 2			
Wire End	Wire Size (mm)	% of Wire on the Reel	Wire Tension (N)	Wire End	Wire Size (mm)	% of Wire on the Reel	Wire Tension (N)
AM				AM			
3	0.97	100	5 - 45	2	0.97	100	5 - 45
4	0.97	40	9 - 53	6	0.97	60	9 - 45
5	0.97	40	5 - 40	7	0.97	60	0 - 40
6	0.97	40	18 - 58	10	0.97	100	18 - 50
7	0.97	40	13 - 40	12	0.98	100	0 - 44
10	1.3	30	45 - 72	13	0.98	100	13 - 36
PM				PM			
3	0.97	70	5 - 45	2	0.97	80	9 - 67
4	0.97	20	9 - 22	6	0.97	100	23 - 53
5	0.97	70	5 - 31	7	0.97	60	18 - 40
6	0.97	70	18 - 53	10	0.97	60	18 - 40
7	0.97	70	13 - 45	12	0.98	60	0 - 32
10	1.3	80	53 - 80	13	0.98	60	5 - 28

Table 6 : Results of the monitoring of line wire tension of selected ends from each line during the plating process.

At times during the taking of the readings the tension increase to over 110 N, which was off the scale of the hand tensometer or drop near to zero. The tension variation was also measured at the end of the plating lines before the take-up and was found to be of identical pattern, tension oscillating from zero to above 110 N. As the tension measurements were similar at either end of the plating line the readings taken before the take-ups (coilers) were not recorded.

8.3 Wire Let-off Control

The poor condition and maintenance of the let-off stands had been highlighted at the beginning of the project. The condition and standard required had been discussed with the management group, highlighting the degradation in the bearings, bushes, break shoes & drum and brake arm return springs and a maintenance plan was devised and implemented

It also came to light, that there was a plan to implement a new brake control system designed by the machinery division at National-Standard, on all of the let-off stand on each plating line but due to a number of other high priority projects the implementation of the new system had been delayed.

The changes proposed by the machinery division, were, to modified the brake control system on each of the let-off ends by replacing the existing simple spring return mechanism with a pneumatic cylinder (see figure 20). The pneumatic cylinder would be attached to the brake arm and frame of the let-off stand and the tension of the wire be maintained by a pneumatic cylinder finely regulating the speed of the reel as the wire is pulled down the plating line. The cylinder also would reduces the sudden movement of the arm, eliminating the snatching and snagging of the brake pads onto the brake drum created when the wire speed has become too fast. With a more even pay off system, the tension through the plating line will become more stable.

A request was put to the management group for a single end was to be modified to trial the new pneumatic system. The new system was to be assess for its ability in controlling the breaking and tension of the wire in a production environment and the ability of the operator to use the new set-up but the investigation came under several constraints. Firstly the modified let-off stand was to be 100% used for production as the capacity of a single end could not be speared and secondly this meant that the experimental straightening roller blocks could not be used which restricted the investigation in validating the conclusions made in chapter 7.

8.4 Axial Twist Results

As the investigation is restricted from using the modified straightening roller, conducting a designed experiments to establish the correlation between axial twist & tension to evaluate the effectiveness of the new pneumatic breaking system, a comparison of axial twist, before and after the modification to the let-off stand was made.

After an initial introduction period to allow all the operators to become familiar with the new system , axial twist results from the plated beadwire were collected over a five week period and compered against a similar five week period before the modification. The axial twist results were correlated into bar charts and are detailed in figure 21. Comparing the two set of axial twist results before and after modification, it shows a dramatic improvement in the amount of twist free wire produced

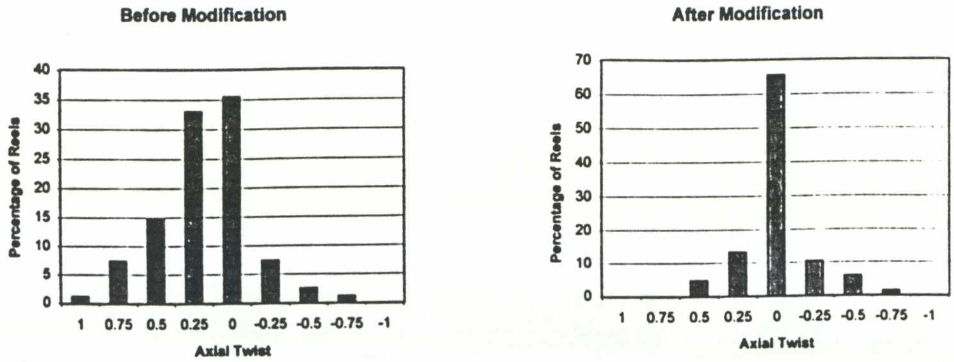


Figure 21 : Results of the comparison of axial twist readings of wire produced before and after the let off stand was modification.

It can be seen from the bar charts that a 50% improvement in wire consistency has been achieved and that there has been a measurable reduction in tension variation, which is illustrated in table 6.

% of Wire on the Reel	Measured Wire Tension (N)
100	13 - 26
90	13 - 32
80	17 - 26
70	17 - 31
60	13 - 26
50	17 - 26
40	17 - 32
30	22 - 32
20	13 - 26
10	13 - 26

Table 7 : Wire tension taken during the production of a reel of 0.965 mm diameter wire produced on the modified let-off stand.

Further work into the correlation of tension and axial twist has to be curtailed as the two year teaching company placement was completed.

8.5 Discussion

The modified let-off stand dramatically reduced the variation in tension and axial twist. The improvements were found to be instantaneous, from the first day of production a reduction of 50% was experienced i.e. the amount of axial twist that deviated from zero. The investigation into the control of tension and its effects on axial twist may have been restricted and the project time been completed but the comparison of axial twist results before and after the braking system was modification has proved the conclusions made in the previous chapters to be correct.

By being able to improve the effectiveness and efficiency of the let-off stand breaking system, it has enabled tension to become more consistent during the plating of a reel of wire and reduce the variation in twist measured. The straightening rollers are used to eliminate twist from the wire but the investigation has shown that it is a combination of factor within the process that effects the in the inducement of axial twist.

The operators can now be confident that after setting the straightening roller blocks to produce twist free wire, measured amount of twist will be the same when the reel has been plated. They have also discovered other benefits with the modifications. The improved effectiveness of the brake system has reduced the instances of the wire braking during processing. This can be attributed to the elimination of the brake pads snatching on the brake drum on the let-off stand. The amount of attention required to the wire as it is being pulled of the reel has also been reduced allowing the operator to more time to prepare and set up wire ends that have completed a reel and requires changing to a fresh reel of bright wire.

Through the modifications to the let-off stand, the degree of twist has been reduced but we still find axial twist deviating from zero in either a clockwise or anticlockwise direction. This has raised the question 'why is twist still found to be either positive or negative when tension within the wire varies and remains positive'? Wire tension will always remain positive as the wire is pulled down & through the plating process, controlled by the let-off stand, braking system. It is the variation in the amount of tension that influences axial twist within the wire.

In chapter 6, a theoretical value of torque was calculated, demonstrating the small amounts force required to twist the wire and it is from this that it can be explain why twist is unidirectional. As tension increases the wire is pulled against the various pulleys and guides within the plater, where the wire touches these points of contact a force is applied. If the force applied to the wire is off set from the vertical to the point of contact, a twist will be applied to the wire. The direction of twist induced will depend on which side of the vertical the force is applied (see figure 17) and as the wire is travelling at over 4 m/s, it is retained to the next point of contact. If the tension remains high the twisting action is repeated.

When the tension in the wire is reduced, the force applied on the wire is also reduced so reducing the amount of induced twist. At the same time the wire may become free from some points of contact allowing the twist to be released and travel along the length of the wire. To enable & ensure twist free wire is produced, the tension within the wire being pulled down the two plating lines must remain constant. It is the variation in tension that is the main factor that reduces the effectiveness of the straightening rollers from achieving twist free wire.

CHAPTER 9

Critical Analysis

9.1 Conclusions

The initial aim of the project is to investigating residual torsion / axial twist through the beadwire production process, to identify the influences of various elements within the process and implement control measures to improve the wire quality. The underlying aim was to remove the 'blackart' of wire making, move towards a more standardised documented approach of the beadwire plating process and to reduce the loss of knowledge when operators left the company or retired.

Researching the axial twist problem produced very little information on the subject either at National-Standard or at Aston University Library, which hampered the beginning of the project. The documentation at National Standard dealt with the work undertaken in previous years by a joint team of USA and UK engineers but the experimentation work carried out, concentrated on one aspect of the beadwire plating process, wire stress relieving process i.e. lead bath and did not look at the whole process & plating system. There was no analysis of the total process to enable the team to justify the benefits of their investigation to reduce axial twist. Their research in the USA and trials within the UK concentrated on one element, the wire guides (sinkers) within the lead bath. A process or the quality of the product can not be improved without having a sound understanding of the key process parameters. The results from their trials did improve & reduce axial twist under controlled experimental conditions, their recommendations were implemented and the wire guides modified. But their conclusions from the trials conducted were not able to cope with production conditions and over a period of time the previous level of axial twist variation had returned.

Experimental design carried out correctly, identifies the most influential process factors from the large number affecting the process performance, optimise them and subsequently improve the system performance. The key benefits of a well design experiment are :

- Understanding the process and product behaviour rapidly.
- Determining the optimal conditions for the process.
- Improving the product and processes to be insensitive to special cause variation.
- Improved process stability and yield.
- Increased profits and return on capital investment.

Work was started investigating the production data to determine if any variation or trends could be identified within the process. It became evident that with the large amount of production data available, there were no significant trends that could be highlighted. Reviewing the project direction it was felt that investigating the whole production process, would not tackle the fundamentals quality problems of axial twist. The initial emphasis of how the wire is made was changed to investigating the root cause of axial twist.

A change in direction to a more analytical and research base project was embarked upon with the use of mathematical models to address the current fundamental problems being faced. Methods of monitoring the wire and axial twist through the process was the first major hurdle in the progression of the project. Various none contact monitoring solutions were researched but found not to be practical, due to the small diameter of the wire, the speed at which the wire travels down through the process and the cost of the specialised equipment needed e.g. a vision system.

The only prescribed procedure to test for axial twist is a simple pull and release method with an observation of the wire to see how far and in which direction the wire rotated at the end of the final process. This limited the amount of analytical work that could be undertaken as the axial twist results at the end of the process can only be recorded visually and the types of experiments that could feasibly be carried out under production conditions restricted due to the environment of the plating process and the health & safety constraints when the equipment is operating. The lack of effective methods for measuring and recording axial twist throughout the process suppressed forward progress until a clear understanding was gained of the particular aspects and mechanics of the problem.

The three areas of work, carried out to obtain data that could be analysed to pin point a probable course of axial twist have, in themselves, have not produced any out right significant results.

Back fitting the test data into the Taguchi array produced the first tangible lead and it was clear that the factors selected did not directly effect axial twist but could be interrelated with its inducement. The Taguchi results were able to discount a number of the factors (test parameters) and indicate the significance of the wire ductility as contributing to the inducement of axial twist and made the investigation take a step back to look at the process from basic first principles.

Where the inter-reactions are unable to be confirmed from the results this may be due to :

- Poor selection of control parameters.
- Factor levels are not set correctly.
- Noise factors have interacted with the experimental results.
- Strong interactive effects exist

A theoretical mathematical model of the problem based on simple Torsion Theory was constructed. Developing this approach enabled an understanding of the problem, a test focused the research on how axial twist is generated within the plating process and is a rearrangement of the torsion equation.

A test to measure the periodic frequency of the wire and thus correlate the modulus of rigidity with axial twist was devised. Low noise level initially caused interference and distorted the results. Once these were overcome and then compering frequency results to axial twist found no correlation, so highlighted that the modulus of rigidity was a minor factor and thus became a constant within the theoretical model.

With ovality being very small this promoted torque as the main reaction in producing axial twist. The main surprise from this work was how a small amount of torque was needed to twist the wire. A theoretical value of the torque needed to twist the wire was calculated at 0.31 Nm and would induced a radial rotation of 2π in the wire in either direction. We had the proof of how twist is introduced, however due to the line design of both platers it was impossible to pinpoint every point along the wire path that would exert a force.

The amount of twist found at the end of the process is controlled by the straightening roller sets through the bending and reverse bending of the wire, known as 'the Buashinger effect' [14], which removes the accumulated twist within the wire. But why does the wire experienced so much variation if the twist is being controlled? Within the process there is some other factor which effect the wire as it is being processed, so affecting the amount of torsion within the wire at any given point or length. The ability of the straightening rollers to produce constant axial twist free wire is being compromised by this influence.

The Taguchi experimentation on the load applied to the wire through the v-grooved rollers and the affect of off-setting specific rollers produced some interesting results. The Taguchi model confirmed the knowledge & experience of the operators in setting up the straightening rollers, highlighting the effect that each of the adjusting bolts (pins) has on the wire. It further showed that the horizontal alignment of the rollers did not have a significant effect on the control of axial twist. The reduced significance of the alignment of the rollers eliminate the effect of the age and condition of the production roller blocks being used.

The load readings highlighted the degree of load variation experienced by the wire as it was pulled through the straightening rollers indicating that another factor which was found to be tension. Tension is the missing link and the key to the problem. Variation in tension; firstly allows induced twist to wonder along the wire in either direction between pinning points. Due to the speed of the wire, a build of twist occurs so when the wire enters the straightening rollers the amount of twist within the wire is different to that when the rollers were originally set. Secondly tension varies the load being applied to the wire, so varying the effectiveness of the straightening rollers. A double hit is scored with a single factor, the wire at any one time, can have large amounts clockwise or anticlockwise twist induced into it. The quality of the wire can be said to have been compromised.

The setting up of the prototype breaking system on one of the production 'ends' enabled an assessment of an improvements in an operational environment and validated the conclusion made during the investigation. The only direct assessment of the improved braking & tension control was by comparing past results with those obtained during the prototype trials but the degree of improvement with constant tension in the wire with little variation proved that tension was the key to controlling axial twist

To summarise the findings and conclusions of the investigation :

- There was only a small amount of literature published on the subject of processing wire down a plating line.

- The US task force team investigating the plating process did not establish the root cause of axial twist and recommended further investigation.

- Wire ductility was identified as a significant factor which contributed to the inducement of axial twist, which opened up further avenues to be investigated i.e. Modulus of Rigidity of the wire.

- The line sampling results and the dissection of the tyre bead did not significantly contribute to the project. The number of rejected tyre bead assemblies that are found at a tyre manufacturer due to axial twist is increased due to the uneven coverage of rubber compound around the wires allowing a wire to break free.

- The periodic frequency test conducted to establish a correlation with axial twist and establish a relationship with modulus of rigidity, found that this was not as significant as first thought and that the modulus of rigidity could be classed as a constant within the theoretical model.

- The monitoring of the load applied to the wires through the straightening rollers was not directly responsible for changes in axial twist within a reel but the variation in load applied was found to be significant. This highlighted wire tension as the key factor which was not previously considered. as playing a part in the inducement of twist.

- Verification of tension as the key factor. Controlled and stable wire tension throughout the processing of a reel enables the straightening rollers to produce near twist free wire.

Chapter 10

Recommendations

10.1 Further Work

The two year project has examined the plating process, analysed the wire and come to a conclusion that the key processing factor is 'Wire Tension'. The initial condition of the plating lines at the start of the investigation is a reflection of the problem, all the lef-off stands were generally in a poor operational condition and the variation in wire tension can partly be contributed to a lack of preventative maintenance. Completing the modifications on the let-off stands; bearings, bushes and washers will enable a quality product to be produced.

Quality equipment does not just refer to the latest technology, it is the standard at which any piece of equipment is maintained and in retrospect, tension variation might not have been highlighted so easily if the equipment was maintained regularly.

The take-up stands at the end of the platers also have tension control, to aid the winding of the wire onto a steel reel. The effect on the straightening rollers from this source of tension variation also requires to be investigated. The effect of tension on the whole beadwire plating system needs to be fully understood

To further the work on axial twist and complete the project, National Standard Company requires to :

- Continue the modification of each let-off stand with the new pneumatic breaking control system.

- Continue the work in correlating the effect of tension variation with the control of axial twist through the straightening rollers.

- Set up for both beadwire platers, a preventative maintenance system. It is important that the preventative maintenance system is implemented, as if the equipment within the plating process returns to the condition when the project started, then quality of the wire will decrease.

Continued research into the processing of tyre beadwire should be considered by National Standard and be conducted on :

- An investigation into axial twist within the bright wire and how it is induced as it is produced by a finished drawing machine. Is axial twist stored within the wire as it drawn down through each block or is it masked as it passes through each die? The degree of variation in axial twist investigated within a reel of bright wire and the effect it has on the amount of twist found at the end of the plating process?

- An investigation into the variance of axial twist in a clockwise and / or anticlockwise during the processing of a reel of wire. Determine the amount of twist induced into the wire at any single point of contact along the plating process against the variation in tension. Is there a difference between the two plating lines, plater one being straight through Vs plater two following a dog leg shape at the end of the process?

- The possibility of setting up an effective close loop control mechanism or system for the adjustment of the straightening rollers. Real time monitoring of tension variation could be monitored at a distance to the straightening rollers and a measure of wire tension could be translated into an adjustment of the setting pins. By the time the wire has reached the straightening rollers, the correct adjustment to achieve zero axial twist would be set within the roller blocks.

APPENDIX 1

- Beadwire Taguchi Model Data & Analysis
    - Taguchi Model Data
    - Taguchi Model Analysis
    - Taguchi Model Results

Taguchi Modeling Data

Batch	*Diameter (mm)*	*U. T. S. (N)*	*Elong'n (%)*	*Torsion (Rev's)*	*0.2% Proof Stress (N)*	*Residual Stress*	*Axial Twist*
20002B	0.965	1459	8.17	67	1240	+5	1/4 A
20001B	0.965	1455	8.03	78	1248	-8	1/2 A
20001D	0.965	1470	8.09	81	1240	+7	1/2 C
18924C	0.966	1490	8.39	72	1257	0	1/4 C
18964B	0.965	1472	7.44	89	1285	-5	1/2 A
18976C	0.965	1460	8.5	53	1259	-1.5	1/2 A
18924B	0.968	1484	8.63	72	1280	-13	1/2 A
18976D	0.965	1479	7.42	76	1238	+5	0
20022D	0.963	1438	7.95	72	1270	-5.5	0
18993C	0.967	1460	8.02	72	1280	-14.5	3/4 A
18964A	0.969	1478	7.87	84	1300	-10	1 A
18993B	0.964	1458	7.68	79	1230	-5	1/2 C
20003B	0.966	1435	7.78	74	1200	+7	1/4 C
19298C	0.963	1425	7.23	89	1220	+25	1/4 C
18853B	0.968	1476	8.67	90	1270	-9	0
20002C	0.965	1464	8.27	85	1260	+3	1/2 A
18993D	0.968	1458	7.80	90	1220	0	1/2 C
20046B	0.963	1452	8.30	67	1265	-6	1/2 C
20046C	0.964	1442	8.20	73	1260	-7	1/2 C
20013A	0.962	1451	8.47	82	1185	-8	1/2 C
20046A	0.961	1456	8.08	64	1235	-13	1/4 C
20022C	0.962	1450	8.32	72	1315	-22	1/4 A
18960C	0.965	1480	8.05	74	1262	-4	1/4C
20074D	0.963	1450	8.47	78	1210	-10	1/2 C
20070C	0.967	1475	7.62	76	1240	-10	1/4 C
21015B	0.963	1445	7.73	76	1210	-2.5	1/4 A
18978A	0.963	1450	8.07	71	1260	-14	0
21015A	0.965	1462	8.50	71	1240	-5	1/4 C
21019C	0.965	1465	8.04	72	1240	-8	0
21030C	0.961	1515	8.32	81	1260	-7	1/4A
20753A	0.964	1515	7.86	78	1285	-7	1/2 C
20754A	0.963	1498	7.63	69	1200	-12	1/4 A
20755C	0.963	1485	8.34	71	1238	-6	1/4 A
21031B	0.963	1458	8.01	67	1220	-6	1/4 C

18409C	0.967	1450	7.77	85	1210	-7	1/2 C
18941C	0.965	1479	8.07	80	1237	-10	1/4 A
18932C	0.961	1490	7.89	77	1239	-3.5	0
18934B	0.965	1425	7.54	82	1220	+2.5	1/4 C
18944C	0.966	1465	7.93	78	1200	-8.5	0
18946A	0.969	1548	7.54	77	1220	+2	1/4 C
18953D	0.962	1464	8.00	82	1200	-7	1/4 C
18911A	0.967	1498	7.99	83	1235	-3	1/4 C
18911B	0.972	1475	8.19	82	1215	-7	1/4 C
18451C	0.967	1450	7.42	78	1195	-7	1/2 A
18451A	0.965	1478	8.25	77	1205	-6	1/4 A
18450	0.965	1450	8.23	86	1230	-9	1/4 C
18929A	0.915	1475	7.66	82	1230	-10	1/4 C
18466A	0.965	1465	7.50	83	1240	-8	0
18944A	0.966	1468	7.59	76	1220	-15.5	1/2 C
18477C	0.967	1460	7.52	62	1200	-2	1/2A
18932B	0.964	1500	7.84	82	1195	0	0
18932D	0.963	1508	8.14	70	1239	-6	1/2 C
18472D	0.965	1467	7.53	74	1101	-3.5	0
18932A	0.964	1458	7.99	90	1200	-12	1/2 C
18853C	0.968	1478	5.84	67	1250	-9	0

Input Variable Key

Taguchi Set	***Diameter***	***U. T. S.***	***Elongation***	***Torsion***	***0.2% Proof Stress***	***Residual Stress***
1	A	B		C		D
2	A		B	C		D
3	A	B			C	D
4		A	B	C		D
5	A		B	C	D	

Taguchi Moldel - Test Results :

Results : 5 Sets of results were obtained assessing a combination of the 6 variables against 2 measures of Axial Twist. First being the actual measured amount of twist from each wire sample, Absolute ie Clockwise or Anti clockwise and the second the actual Deviation from Zero recorded ie 0.25, 0.5, 0.75 etc.

Set 1 (16 by 16) : Diameter, UTS, Torsion, Residual Stress.

Deviation from Zero - UTS (-ve), Diameter (-ve).

Absolute - Torsion (+ve).

Set 2 (8 by 8) : Diameter, Elongation, Torsion, Residual Stress.

Deviation from Zero - Elongation (+ve).

Absolute - Diameter (-ve), Diameter x Elongation (+ve), Torsion (+ve), Residual Stress (+ve).

Set 3 (8 by 8) : Diameter, UTS, 0.2% Proof Stress, Residual Stress.

Deviation from Zero - 0.2% Proof Stress (+ve), Residual Stress (-ve), Diameter x Proof Stress (+ve), UTS x Proof Stress (+ve), UTS (-ve).

Absolute - Diameter (-ve), UTS x Proof Stress (+ve), Diameter x UTS (+ve).

Set 4 (8 by 8) : UTS, Elongation, Torsion, Residual Stress.

Deviation from Zero - Elongation (+ve), Torsion (+ve), Elongation x Torsion (-ve).

Absolute - UTS (-ve), Torsion (+ve), UTS x Elongation (-ve).

Set 5 (16 by 16) : Diameter , Elongation, Torsion, 0.2% Proof Stress.

Deviation from Zero - Elongation x Torsion x Proof Stress (-ve),
Torsion (+ve), Elongation x Torsion (-ve).

Absolute - Diameter (-ve), Torsion x Proof Stress (-ve),
Proof Stress (-ve).

Taguchi Model Results : Set 1A

COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.121875	-.1526	.3013461	-.1372375
2	-.0375	6.775007E-03	7.841106E-03	2.213751E-02
3	-.05	.019275	1.919611E-02	.0346375
4	.0921875	-.1229125	.1850721	-.10755
5	-.025	-.005725	1.486102E-03	9.637498E-03
6	.0625	-.093225	9.700111E-02	-.0778625
7	.0578125	-.0885375	8.567329E-02	-.073175
8	.021875	-.0526	2.218611E-02	-.0372375
9	.0671875	-.0979125	.109032	-.08255
10	.1046875	-.1354125	.2305921	-.12005
11	-.1	.069275	.1146161	.0846375
12	-.1078125	.0770875	.136752	.09245
13	.0296875	-.0604125	3.247204E-02	-.04505
14	-.0296875	-1.037501E-03	3.283292E-03	.014325
15	-.1203125	8.958749E-02	.1762321	.10495

CENTRE OF EQUATION = -1.536249E-02
STANDARD DEVIATION = .2950255
Ok

Taguchi Model Results : Set 1B

COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.29175	.37275	.026244	.0405
2	.427625	.236875	.1455422	-9.537499E-02
3	.3335	.331	2.500003E-05	-1.250001E-03
4	.37175	.29275	2.496401E-02	-3.950001E-02
5	.370375	.294125	2.325625E-02	-.038125
6	.32825	.33625	2.560003E-04	4.000003E-03
7	.3195	.345	2.601001E-03	.01275
8	.339125	.325375	7.562511E-04	-6.875005E-03
9	.308625	.355875	8.930244E-03	2.362499E-02
10	.33525	.32925	1.439993E-04	-2.999993E-03
11	.266375	.398125	6.943225E-02	.065875
12	.313875	.350625	5.402251E-03	.018375
13	.2675	.397	6.708101E-02	.06475
14	.381625	.282875	3.900625E-02	-.049375
15	.339875	.324625	9.302497E-04	-7.624999E-03

CENTRE OF EQUATION = .33225
STANDARD DEVIATION = .1868262
Ok

Taguchi Model Results : Set 2A

COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.0875	-.166725	.1292607	-.1271125
2	-.07915	-7.499941E-05	1.250571E-02	.0395375
3	-.125075	.04585	5.843072E-02	8.546251E-02
4	.08335	-.162575	.1209582	-.1229625
5	-.037575	-.04165	3.321125E-05	-.0020375
6	-.037575	-.04165	3.321125E-05	-.0020375
7	-.125075	.04585	5.843071E-02	8.546249E-02

CENTRE OF EQUATION = -.0396125

STANDARD DEVIATION = .2328864

Ok

Taguchi Model Results : Set 2B

COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.30425	.37525	.010082	.0355
2	.27925	.40025	.029282	.0605
3	.31675	.36275	4.232004E-03	2.300001E-02
4	.3585	.321	2.812499E-03	-.01875
5	.321	.3585	2.812499E-03	.01875
6	.346	.3335	3.125002E-04	-6.250002E-03
7	.37525	.30425	.010082	-.0355

CENTRE OF EQUATION = .33975
STANDARD DEVIATION = 9.228476E-02
Ok

Taguchi Model Results : Set 3A

COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.307375	-.0794	.2991898	-.1933875
2	.0105	.217475	8.567729E-02	.1034875
3	.146725	.08125	8.573951E-03	-.0327375
4	-.015625	.2436	.1343952	.1296125
5	.21435	.013625	8.058106E-02	-.1003625
6	-.051275	.27925	.2184936	.1652625
7	.09985	.128125	1.598951E-03	.0141375

CENTRE OF EQUATION = .1139875
STANDARD DEVIATION = .3440328
Ok

Taguchi Model Results : Set 3B

COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.338625	.3759	2.778853E-03	1.863751E-02
2	.398	.316525	1.327635E-02	-4.073749E-02
3	.270775	.44375	.0598407	.0864875
4	.403125	.3114	1.682695E-02	-.0458625
5	.30715	.407375	.0200901	.0501125
6	.310275	.40425	.0176626	.0469875
7	.43015	.284375	.0425007	-.0728875

CENTRE OF EQUATION = .3572625
STANDARD DEVIATION = .157197
Ok

Taguchi Model Results : Set 4A

COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.1927	-.0677	.1356163	-.1302
2	.078125	.046875	1.953125E-03	-.015625
3	-.041675	.166675	8.681945E-02	.104175
4	.145825	-.020825	5.554445E-02	-.083325
5	.109375	.015625	1.757813E-02	-.046875
6	.03645	.08855	5.428821E-03	.02605
7	.0625	.0625	6.938894E-18	-9.313226E-10

CENTRE OF EQUATION = .0625
STANDARD DEVIATION = .2080317
Ok

Taguchi Model Results : Set 4B

COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.30105	.2448	6.328127E-03	-.028125
2	.165625	.380225	9.210632E-02	.1073
3	.166675	.379175	9.031251E-02	.10625
4	.291675	.254175	2.812499E-03	-.01875
5	.259375	.286475	1.468821E-03	.01355
6	.3323	.21355	2.820313E-02	-5.937501E-02
7	.25	.29585	4.204447E-03	2.292501E-02

CENTRE OF EQUATION = .272925
STANDARD DEVIATION = .1794578
Ok

APPENDIX 2

- Beadwire Process - Line Sample Exercise Results

Plater 2 : Process Wire Material Results

Wire End : 15 Wire Dia : 0.965 Batch No : 22224B Date of Sample : 23-6-93

Sample No	Diamater (mm)	Ovality (mm)	Breakload (N)	Elongation	0.2% Proof Stress	U.T.S. (N)	Residual Stress	Axial Twist	Straight -ness	Commemts Sample Length
1	0.969	0.008	1451	2.42	1280	1451	+4	1C	20° CAST	9m
2	0.980	0.002	1336	8.48	1278	1340	+16	½C	F/SINKERS	10m
3	C	C	1356	8.18	1320	1360	+10	½C	[illegible]	19m
4	C	C	1380	2.65	1260	1284	C	¼C	[illegible]	10m
5	0.964	0.004	1358	8.58	1320	1362	+15	¼C	[illegible]	9m
6	0.962	0.003	1356	8.38	1318	1360	+18	0	F/DOGLEG	11.5m
7	0.959	0.001	1359	7.61	1324	1364	+24	1¾C	1	15m
9	0.966	0.002	1359	7.48	1174	1364	+11	½C	¼	REEL

Wire End : 13 Wire Diameter : 0.965 Batch No : 22230B Date of Sample : 23-6-93

Sample No	Diamater (mm)	Ovality (mm)	Breakload (N)	Elongation	0.2% Proof Stress	U.T.S. (N)	Residual Stress	Axial Twist	Straight -ness	Commemts Sample Length
1	0.969	0.009	1474	3.06	1300	1480	+3	1¾C	20° CAST	11m
2	C	C	1205	7.26	1145	1210	+10	0	F/SINKERS	10m
3	0.981	0.002	1387	8.00	1350	1392	+25	2¼C	[illegible]	19m
4	0.957	0.002	1388	8.10	1340	1393	+20	1C	[illegible]	10m
5	0.967	0.002	1385	8.02	1341	1390	+20	¾C	1	9m
6	0.966	0.005	1388	9.03	1322	1394	+25	0	[illegible]	11.5m
7	0.966	0.004	1385	8.41	1341	1389	—	½C	1	13m
9	0.963	0.003	1385	8.48	1198	1390	+1	¼A	0	REEL

Plater 2 : Process Wire Material Results

Sheet 2 of 4

Wire End : 17 Wire Dia : 0·965 Batch No : 22212 C Date of Sample : 24-6·92

Sample No	Diamater (mm)	Ovality (mm)	Breakload (N)	Elongation	0.2% Proof Stress	U.T.S. (N)	Residual Stress	Axial Twist	Straight -ness	Commemts Sample Length
1	0·972	0·004	1481	2·68	1357	1481	+6	1/4 A	22" Cast	7 m
2	c	c	1367	8·39	1318	1371	+23	—	F/Sinkers	10 m
3	c	c	1383	8·30	1339	1386	+14	0	~ (1)	19 m
4	c	c	1358	5·31	1318	1360	c	1/4 c	~	10 m
6	0·970	0·004	1383	8·54	1317	1390	+17	0	20°C.::	11·5m
7	0·968	0·003	1386	8·52	1340	1391	+19	1/2 c	1	17m
9	0·968	0·001	1386	7·78	1205	1386	+11	1/4 A	1/4	REEL

Wire End : 9 Wire Diameter : 0·965 Batch No : 423270 Date of Sample : 22-6-93

Sample No	Diamater (mm)	Ovality (mm)	Breakload (N)	Elongation	0.2% Proof Stress	U.T.S. (N)	Residual Stress	Axial Twist	Straight -ness	Commemts Sample Length
1	0·963	0·000	1917	3·06	1640	1917	+10	1/4 c	20" Cast	15 m
2	c	c	1623	7·02	1460	1623	c	0	F/Sinker	10 m
3	0·945	0·002	1591	7·20	1460	1691	+28	3/4 c	~	19 m
4	0·964	0·000	1664	7·68	1522	1678	+17	1/4 A	~	10 m
5	0·958	0·000	1672	7·92	1529	1678	+30	1/2 c	~	9 m
6	0·969	0·002	1668	8·12	1520	1673	+19	0	1	11 5m
7	0·958	0·000	1669	7·90	1525	1674	+24	1A	1/2	9 m
9	0·954	0·004	1670	7·58	1398	1676	+20	0	1/2	REEL

Plater 2 : Process Wire Material Results

Sheet 3 of 4

Wire End : 8 Wire Dia : 0·97 Batch No : Date of Sample : 16 - 6 - 93

Sample No	Diamater (mm)	Ovality (mm)	Breakload (N)	Elongation	0.2% Proof Stress	U.T.S. (N)	Residual Stress	Axial Twist	Straight-ness	Commemts Sample Length
1	0·963	0·006	1915	2·95	1740	1915	+7	–	20' Cast	16m
2	0·962	0·004	1684	8·34	1519	1690	C	0	F/Sinkers	10m
3	0·976	0·000	1707	7·62	1561	1712	+7	1/2A	0	19m
4	0·961	0·004	1590	4·25	1500	1590	C	1/4A	1/2	9m
5	0·968	0·010	1721	8·09	1580	1724	+12	–	1	10m
6	0·964	0·006	1720	8·14	1500	1724	+10	0	~	11·5m
7	0·963	0·006	1722	8·37	1595	1725	+11	1/2A	3/4	8m
9	0·963	0·007	1719	8·21	1508	1719	+6	3/4C	0	Reel

Wire End : 5 Wire Diameter : 0·97 Batch No : 42248A Date of Sample : 18 - 6 - 93

Sample No	Diamater (mm)	Ovality (mm)	Breakload (N)	Elongation	0.2% Proof Stress	U.T.S. (N)	Residual Stress	Axial Twist	Straight-ness	Commemts Sample Length
1	0·953	0·000	1880	2·97	1780	1880	–	1 1/4	20' Cast	19m
2	0·950	0·002	1565	7·72	1400	1568	–	0	F/Sinkers.	10m
3	0·969	0·000	1548	5·74	1402	1550	–	1/4C	~	19m
4	C	C	1603	8·08	1441	1603	–	0	~	9m
5	0·960	0·003	1603	7·62	1441	1603	–	0	~	10m
6	0·957	0·000	1601	8·48	1433	1603	–	0	1	11·5m
7	0·960	0·004	1603	8·26	1438	1604	–	?	1/2	5m
8	0·955	0·000	1603	8·15	1262	1603	–	1/2A.	–	– · From S/Rollers
9	0·954	0·000	1603	·92	1290	1605	–	1/2A	1/2	Reel

Plater 2 : Process Wire Material Results

Sheet 4 of 4

Wire End : 6 Wire Dia : 0·965 Batch No : 42238A Date of Sample : 16-6·93

Sample No	Diamater (mm)	Ovality (mm)	Breakload (N)	Elongation	0.2% Proof Stress	U.T.S. (N)	Residual Stress	Axial Twist	STRAIGHT -NESS	Commemts SAMPLE LENGTH
1	–	–	1919	3·06	1600	1919	–	1/4 A	20°CAST	18m
2	–	–	1374	6·21	1232	1374	–	1/4 A	F/SINKERS	10m
3	–	–	1625	8·10	1460	1628	–	1 A	~	19m
4	–	–	1642	5·45	1500	1642	–	1A	1	9m
5	–	–	1672	8·33	1520	1677	–	1/2 A	1/2	10m
6	–	–	1676	8·32	1520	1680	–	1/4 C	~	11·5m
7	–	–	1679	7·88	1540	1681	–	1/4 C	1 1/4	6m
8	–	–	1672	7·90	1468	1677	–	1/2 A		–
9	–	–	1681	8·52	1461	1683	–	0	0	REEL

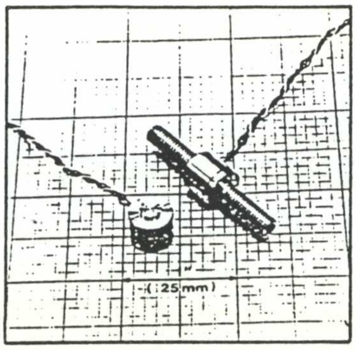
Wire End : 19 Wire Diameter : 1·65 Batch No : 22312D Date of Sample : 24-6·93

Sample No	Diamater (mm)	Ovality (mm)	Breakload (N)	Elongation	0.2% Proof Stress	U.T.S. (N)	Residual Stress	Axial Twist	STRAIGHT -NESS	Commemts SAMPLE LENGTH
1	1·650	0·005	4098	4·44	3375	4148	–	1/2 C	22°CAST	5m
2	<	<	3612	8·18	3120	3612	–	0	F/SINKERS	10m
3	<	<	3899	5·34	3500	3905	–	1/4 C	~ (1)	19m
4	<	<	4059	7·94	3575	408[illegible]	–	1/2 C	~ (1)	9m
5	1·647	0·003	4071	8·30	3575	4071	–	?	~	10m
6	1·645	0·000	4070	9·67	3555	4080	–	0	~ 20°	11·5m
7	1·643	0·002	4079	7·70	3095	4103	–	1/4 A	1	19m
9	1·642	0·004	4079	8·64	3060	4092	–	1/2 C.	1/4	REEL

APPENDIX 3

- Load Cell - Technical Data

Entran®



"OFF-THE-SHELF" STOCK PROGRAM

ELH Series
Miniature High-Accuracy Load Cells

- 0.4" (10mm) TO 0.79" (20mm) DIAMETERS
- 2 LB TO 3000 LB (10N TO 15000N) RANGES
- STATIC AND DYNAMIC RESPONSE

Entran's ELH Miniature High-Accuracy Series Load Cells are a state-of-the-art achievement in miniature load cell design from our International facilities. Developed with the user in mind, the ELH offers an optimum combination of characteristics which permit force or weight measurements where small size and accuracy are of prime importance. The ELH is constructed from stainless steel in 4 housing configurations for maximum flexibility.

Equally suitable for compression and/or tension forces the ELH series meet most requirements from aerospace to industrial and robotic uses. Due to its small size and absence of internal flexures, off axis loading and mounting torques cannot be tolerated. The ELH is a load cell which utilizes a fully active semiconductor bridge and provides full scale outputs as high as 200mV. The semiconductor circuitry is fully compensated for temperature changes in the environments, and possesses excellent thermal characteristics.

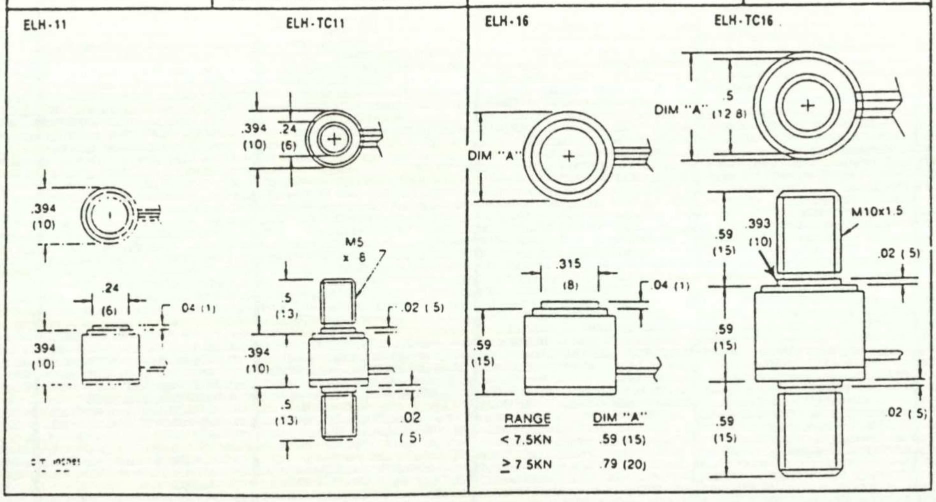
Entran Specification FELHS-591B

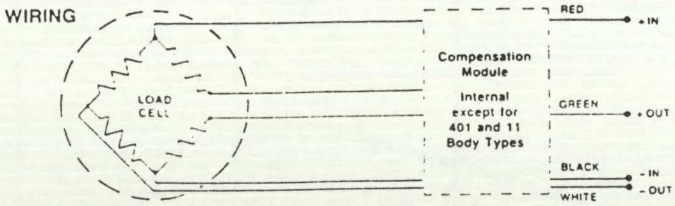
METRIC SERIES

MODEL	ELH-11 and ELH-TC11							ELH-16 and ELH-TC16					
RANGE[3] N	10	20	50	• 100	200	• 500	750	• 1K	2.5K	• 5K	7.5K	• 10K	15K
OVERRANGE[3] N	20	40	100	200	400	1000	1500	1.5K	3.75K	7.5K	10K	15K	22.5K
SENSITIVITY[3] mV/N	6	3	2	1	0.5	0.2	0.13	0.2	0.08	0.04	0.026	0.02	0.013
COMPLIANCE[4, 5]	DEFLECTION: < 20μm F.S. typ. USEFUL FREQ.: >1000 Hz typ.												

[1] Zero offset of ± 15mV typ. at 80°F (26°C) after warm-up. Lower values available on request. [2] Other Excitations and Temperature Ranges available on request. [3] Must be loaded perpendicular and on center distributed over loading surface. [4] Deflection is for active surface of load cell and assumes fully supported reaction surface. [5] Frequency is for unloaded unit and only for models without threaded mounting studs.

NON-LINEARITY	±0.5%F.S	INPUT IMPEDANCE nom.	1500 Ω nom typ (450Ω min)
HYSTERESIS	±0.5%F.S	OUTPUT IMPEDANCE nom.	500 Ω nom
THERMAL ZERO	±1%F.S./100°F (±1%F.S./55°C)	EXCITATION	[2] 15 V DC
THERMAL SENSITIVITY	±2%/100°F (±2%/55°C)	COMPENSATED TEMP.	[2] 20°C to 80°C OPTION Z 0°C to 60°C
MODE	ELH Compression only ELH-TC Tension & Compression	OPERATING TEMP.	[2] -40°C to +121°C





OPTION "/5"

5 WIRE OUTPUT FOR ZERO OFFSET ADJUST
+Output is split into 2 wires, Green and Blue. User connects a 25 Ω potentiometer across Green and Blue with center tap as + output.
Example: ELH-401/5-

HOW TO ORDER: ELH — TC401 — 100 Z

ELH	TC401	100	Z
Series	Body Type	Range	Temp. Comp. Option

Units (lbs. or N) Match Body

• OFF-THE-SHELF STOCK

Specifications subject to change without notice

APPENDIX 4

- Straightening Roller - Experimental Design
    - Experimental 16X16 Array
    - Straightening Roller Experimental Results
    - Taguchi Model Results

Taguchi Experimental Design
Straightening Rollers, 16X16 Array.

	Experiment Settings									
Test Number	Pin 1 (Turn)	Pin 2 (Turn)	Pin 3 (Turn)	Pin 4 (Turn)	Roller 2H (adjus'nt)	Roller 5H (adjus'nt)	Roller 5V (adjus'nt)	Roller 2V (adjus'nt)	Axial Twist (Response) [No. of Tuns]	Wire Diameter (mm)
1	+ 0.25	- 0.25	- 0.25	- 0.25	+ 0.75	- 0.75	+ 0.75	- 0.75	1.5 AC	0.964
2	+ 0.25	+ 0.25	- 0.25	- 0.25	- 0.75	+ 0.75	- 0.75	+ 0.75	1.75 AC	0.964
3	+ 0.25	+ 0.25	+ 0.25	- 0.25	+ 0.75	- 0.75	- 0.75	- 0.75	3.5 AC	0.964
4	+ 0.25	+ 0.25	+ 0.25	+ 0.25	+ 0.75	+ 0.75	- 0.75	+ 0.75	6.5 AC	0.964
5	- 0.25	+ 0.25	+ 0.25	+ 0.25	- 0.75	+ 0.75	+ 0.75	- 0.75	1.24 AC	0.964
6	+ 0.25	- 0.25	+ 0.25	+ 0.25	- 0.75	- 0.75	+ 0.75	+ 0.75	0.25 AC	0.965
7	- 0.25	+ 0.25	- 0.25	+ 0.25	+ 0.75	- 0.75	- 0.75	+ 0.75	2.5 AC	0.964
8	+ 0.25	- 0.25	+ 0.25	- 0.25	- 0.75	+ 0.75	- 0.75	- 0.75	2.75 AC	0.963
9	+ 0.25	+ 0.25	- 0.25	+ 0.25	- 0.75	- 0.75	+ 0.75	- 0.75	0.25 C	0.965
10	- 0.25	+ 0.25	+ 0.25	- 0.25	- 0.75	- 0.75	- 0.75	+ 0.75	0.25 C	0.965
11	- 0.25	- 0.25	+ 0.25	+ 0.25	+ 0.75	- 0.75	- 0.75	- 0.75	3.0 AC	0.964
12	+ 0.25	- 0.25	- 0.25	+ 0.25	+ 0.75	+ 0.75	- 0.75	- 0.75	1.25 AC	0.966
13	- 0.25	+ 0.25	- 0.25	- 0.25	+ 0.75	+ 0.75	+ 0.75	- 0.75	0.5 AC	0.965
14	- 0.25	- 0.25	+ 0.25	- 0.25	+ 0.75	+ 0.75	+ 0.75	+ 0.75	1.75 AC	0.965
15	- 0.25	- 0.25	- 0.25	+ 0.25	- 0.75	+ 0.75	+ 0.75	+ 0.75	1.25 C	0.965
16	- 0.25	- 0.25	- 0.25	- 0.25	- 0.75	- 0.75	- 0.75	- 0.75	0.5 C	0.965

Notes : Axial Twist – C = Clockwise Rotation, AC = Anticlockwise Rotation.
Each pin was adjusted by a quarter of a turn, each roller was adjusted 0.75 mm from its original position on the roller plate.

Taguchi Experimental Design
Straightening Rollers – Load Cell Data

	Load Cell Readings							
	Pin 1		Pin 2		Pin 3		Pin 4	
Test Number	Recorder Reading (Mv)	Load (N)	Recorder Reading (Mv)	Load (N)	Recorder Reading (Mv)	Load (N)	Recorder Reading (Mv)	Load (N)
1	10	250	0	0	68	1700	0	0
2	21	525	0	0	31	725	7	175
3	48	1200	0.4	10	32	800	6.4	160
4	19	475	0.4	10	84	2.14	5	125
5	19	475	0.4	10	31	775	4	100
6	9	225	6.4	160	80	2000	5	125
7	39	975	0.4	10	90	2250	1	25
8	10	250	0	0	160	4000	0	0
9	49	1220	16	400	104	2600	0	0
10	15	375	13	325	172	4.300	5.2	130
11	32.8	820	2	50	120	3000	11	275
12	54	1350	5	125	84	2100	1.6	40
13	62	1550	6.8	170	158	3950	2.4	60
14	21.2	530	2	50	97	2425	1	25
15	32	800	2	50	70	175	1	25
16	32	800	3.2	80	116	2900	12	300

Taguchi Model Results : Straightening Rollers

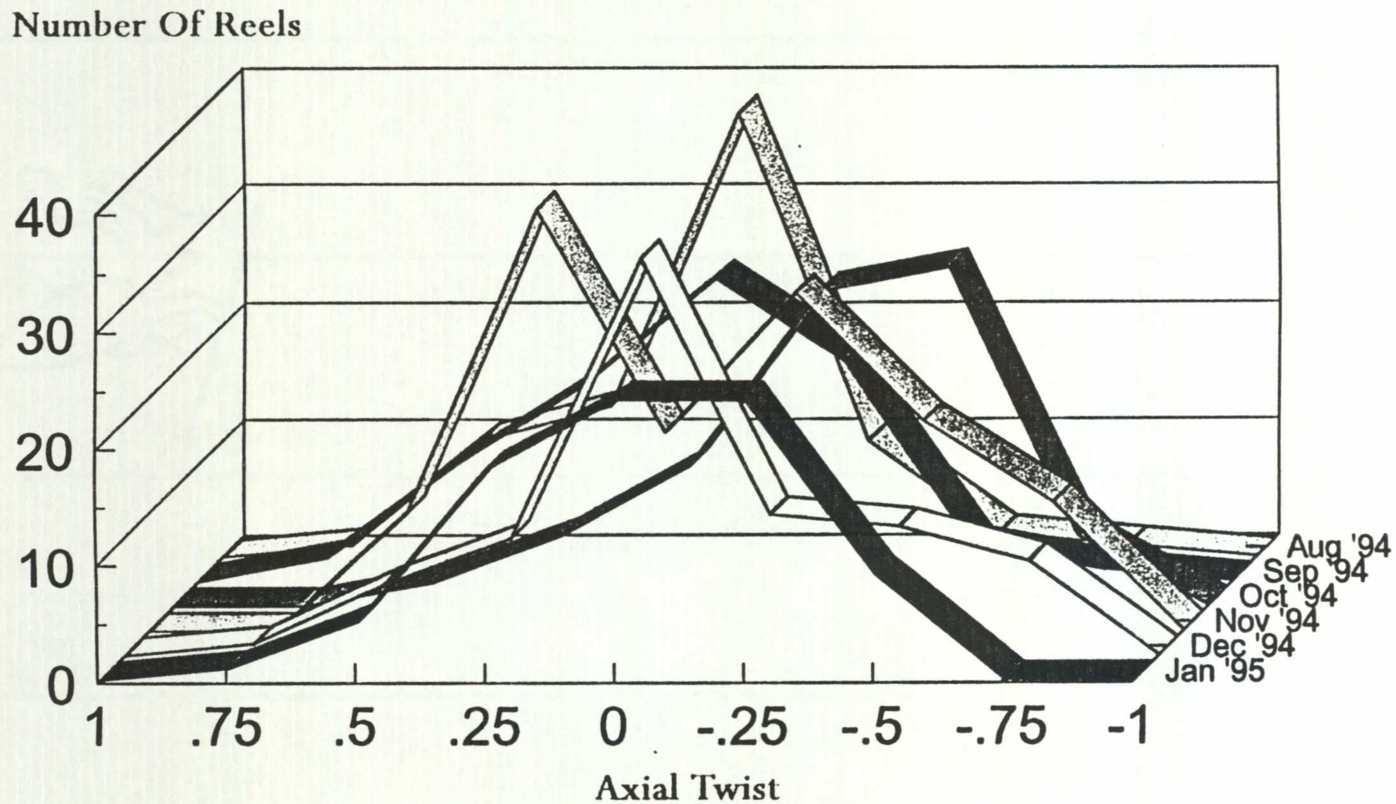
COLUMN NUMBER	MEAN LOW	MEAN HIGH	SQUARE OF SUM	COEFF
1	.2953125	.3265625	3.90625E-03	.015625
2	.2953125	.3265625	3.90625E-03	.015625
3	.2239625	.3979125	.1210344	.086975
4	.2989625	.3229125	2.294409E-03	.011975
5	.340625	.28125	1.410156E-02	-.0296875
6	.30365	.318225	8.49723E-04	7.287503E-03
7	.26615	.355725	3.209472E-02	.0447875
8	.37865	.243225	7.335972E-02	-.0677125
9	.31615	.305725	4.347226E-04	-5.212501E-03
10	.2625	.359375	3.753906E-02	.0484375
11	.3333375	.2885375	8.028159E-03	-.0224
12	.2833375	.3385375	1.218816E-02	.0276
13	.2953125	.3265625	3.90625E-03	.015625
14	.4203125	.2015625	.1914063	-.109375
15	.328125	.29375	4.726562E-03	-.0171875

CENTRE OF EQUATION = .3109375
STANDARD DEVIATION = .1973619
Ok

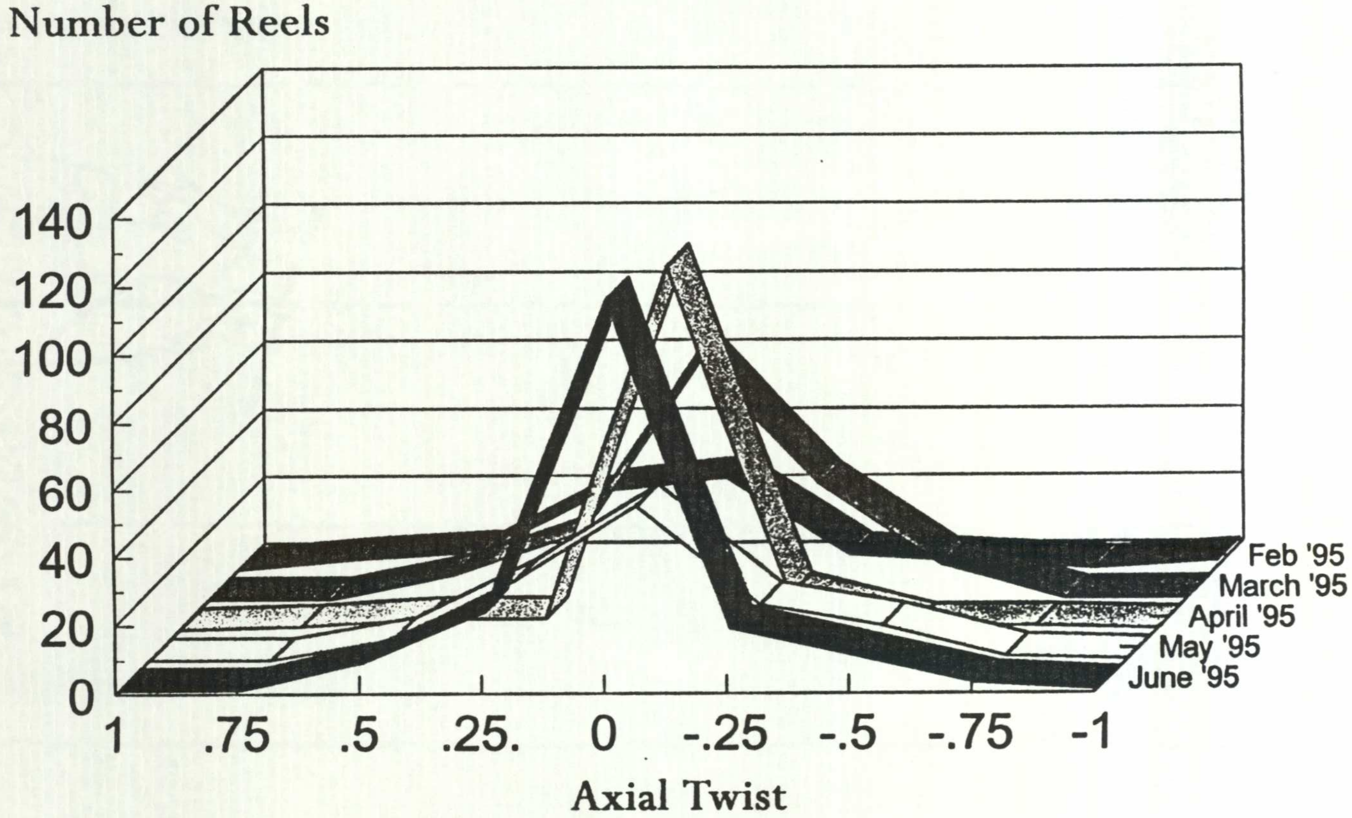
APPENDIX 5

- Beadwire Tension Verification - Axial Twist Results Before and After the Let-Off Stand was Modified.

Occurance of Axial Twist Before The End Was Modified



Modified Take-up



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