Effects of rolling parameters on the shape of cold rolled strip.

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Effects of Rolling Parameters on the Shape of Cold Rolled Strip.

Philip James Benstead

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February 1993

COLLABORATING ORGANISATION

LEE STEEL STRIP LTD.,

MEADOWHALL,

SHEFFIELD.

A TEACHING COMPANY SCHEME PROGRAMME.

PREFACE

The work described in this thesis was carried out as part of a "Teaching Company Scheme" programme. The programme was joint funded by SERC/DTI and Lee Steel Strip Ltd. of Sheffield.

Sheffield City Polytechnic and Lee Steel Strip Ltd. were jointly involved in the work which was carried out between the October 1989 and October 1991.

Dr. R. P. Stratton of Sheffield Hallam University was the academic supervisor and Dr. R. A. Hooper the industrial supervisor, for the teaching company programme.

Mr. A. G. Evans of Sheffield Hallam University and Mr K. Meadows of Lee Steel Strip also assisted with supervision.

Supporting Studies continued during the work, these included personal tuition in the use of "Taguchi" statistical experimental design techniques by Mr J. Callender of Sheffield City Polytechnic, and attendance at the conferences:

"Rolling" hosted by The Institute of Metals at Imperial College, London. 1990 and "Mathematical Modelling of Rolls", hosted by the Institute of Metals, London 1991.

DECLARATION

During the period of registration for the CNAA degree of MPhil. the candidate has not been registered for any other CNAA award of for a university degree.

The results and theories presented in this thesis are original except where reference is made to previous work.

Signed: Date:

P. J. BENSTEAD

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We aknowledge Fulmer Materials Technology, formerly BNF(metals) (British Non-Ferrous Metals) for advice, and help with measuring equipment for measuring strip shape.

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EFFECTS OF ROLLING PARAMETERS ON THE FLATNESS AND SHAPE OF COLD ROLLED STRIP.

ABSTRACT

Various experimental methods have been used to show the effect of different Sendzimir mill rolling parameters on stainless steel strip shape. Experiments using sister coils, noting the effects of change over a number of coils, and using the "Taguchi" statistical experimental design techniques have been carried out. Work has been carried out on individual rolling presses and on complete rolling sequences.

Strain measurements have been used to show the behaviour of a statically loaded work roll, and the vertical and horizontal bending of a roll were investigated. From this work the effects of the axially adjustable first intermediate rolls on the strip shape have been further investigated.

The parameters that affect strip shape have been identified and stated in order of the magnitude of their effect. The adjustments that are needed to improve specific strip shape defects have been identified. It has been established where rolling parameter alterations have an interacting effect with other rolling parameters. Recommendations have been made that will improve the rolling process to enable a more consistent and better product, over a limited material range, to be rolled.

Consideration has been given to new roll shapes and roll bending has been related to specific strip shape. Recommendations have been made to improve the rolling process so as to attain flatter strip.

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1.0 INTRODUCTION

Strip shape, also referred to as strip flatness, is becoming more of a concern for all involved in the rolling industry. Poor strip shape can increase scrap because, products made from strip with poor shape can be defective. With the increasing speed and sophistication of process lines, poor shape feed stock can damage machinery or slow down production.

Strip shape becomes increasingly difficult to control as the width to thickness ratio increases[1] and also as the material becomes harder.
It is generally accepted that strip shape defects are caused by a differential percentage reduction across the strip width. This causes a differential elongation of adjacent portion of strip, which sets up internal stresses, leading to buckling [2].

There are four major strip shape defects produced be differential reductions, these are termed:

Loose (wavy) edges.

Quarter buckle.

Centre fullness.

Herringbone (ripple).

Examples of these defects and their associated stress patterns are shown in Figure 1.

There are three types of strip shape defects not generally associated with the differential reductions, these are termed:

Cross camber.

Coil set.

Twist.

Examples of these defects and their associated stress patterns are shown in Figure 2.

In all rolling mills there are a large number of variables (parameters) which can affect strip shape. Most individual rolling mills have slightly different operating characteristics. Much work published with regards to strip shape control is concerned with individual mills.[3]

The aims of this work are:

a) To investigate the major parameters which affect strip shape on a Sendzimir 20-high cluster mill used to roll thin, hard stainless steel.

b) To optimised the rolling parameters so that the "best" strip shape is available.

Use is made of a "Taguchi" statistical experimental design technique [4] as an aid to highlighting the major parameters affecting strip shape. This technique is also used to predict the best rolling parameter settings that optimise flatness.

Static strain analysis of a loaded work roll was carried out to understand the bending behaviour of a work roll. This bending is related to strip shape defects. From the understanding gained, ideas for optimising rolling parameters will be drawn.

The mill on which the research has been carried out is a Sendzimir rolling mill ZR23B-19 situated at Lee Steel Strip Ltd., Meadowhall, Sheffield.
The mill rolls Stainless, and Special Texture steel, the mill width is 483mm (19") and its range of gauge is 3.0 - 0.05mm. Reductions of up to 90% are often given to the materials.

Research has been carried out on a variety of material types. Initial work concentrated on a steel of type 301S21 Cr Ni 17/7 Austenitic Stainless. This steel was chosen because of its rapid work hardening characteristics due to its ease of transformation to martensite, it being a semi stable austenitic steel.

Because of its hardness and the thin gauge often required from this product, it was more sensitive to strip shape problems. Typical dimensions are:

Widths up to 460mm (18")

Thicknesses down to 0.05mm (0.002")

Work was also conducted on other austenitic material. Due to the lack of sufficient 301S21 stainless processed. Other materials tested are 314S16 CR Ni 18/10, 0.06C and 316S16 Cr Ni Mo 17/11/2.5, 0.07C.

Tests were carried out on a variety of widths depending on the availability of material. Each set of tests were kept within a narrow range of dimensional differences and these are stated with the work.

2.0 LITERATURE SURVEY

2.1 STRIP SHAPE MEASUREMENT

The two major definitions of strip shape are a follows:

a) Strip shape is "a variation in reduction across the width of a strip, this leads to a mismatch in elemental strip lengths such that distortion occurs when these lengths have to fit into their boundary conditions".[1]

b) Strip shape is "the difference in longitudinal speed of the metal, as it leaves the roll bite, across the width of the strip".[5]

Most of the work which has been carried out by researchers, uses the first definition stated. A quantitive evaluation of strip shape was forwarded by Pearson [6] in which shape was defined in dimensionless units referred to as the "MON". The "Mon" is the fractional difference in lengths of adjacent width sections.

$$\text{Shape}_{\text{MONS}} = \frac{\Delta L}{L} \times 10^{-4}$$

L=length of the shortest portion of strip

ΔL=difference in length between the shortest and longest portions of strip

Later work [7] introduced a more sensitive quantification of strip shape, the I unit, this is based on the same formula forwarded by Pearson. The "I-unit" is a factor of ten times more sensitive than the "Mon".

10I units = 1 Mon

Strip shape may be "Latent" or "Manifest". Latent shape is that which is not visible. Strip shape can be described as latent if the strip is held under tensions of such a magnitude that it is pulled flat. When the tension is released, the strip will resume its manifest shape. Strip shape is sometimes referred to as latent when the second moment of area of the strip (I) , and Youngs modulus (E) are large enough to enable the internal stress distribution to be held without causing buckling [8,9]. In this case subsequent slitting of the strip may release the latent shape to cause "Manifest" shape due to the strip geometry alteration.

There are two basic areas of stress patterns which can affect strip shape [10]:

a) Longitudinal stress patterns across the width of the strip.

b) Through the thickness stress patterns.

The longitudinal stress patterns are created by a mismatch between the cross-sectional profile of the strip and the roll gap. These stress patterns produce poor strip shape, of which typical defects are:

Loose edges.

Full centre.

Quarter buckle.

Herringbone

or combinations of the above. (Figure 1)

Through the thickness stress patterns which are not symmetrical will give rise to typical strip shape defects [11] of:

Coilset

Crosscamber

(Figure 2)

Strip shape measurement can be subdivided into two areas, those of off-line and on-line. Off-line measurement quantifies strip shape in its relaxed form. On-line techniques measure in a dynamic situation. The measurement techniques are varied to suit the particular need of the involved parties. Various Standards Institutes have lists of flatness tolerances for different gauge and width materials [12-15]. Certain measures of flatness are taken using devices such as Straight Edges, Rulers, and Feeler Gauges. These methods are not very accurate and are only really of value on thicker materials which are not distorted by contact. Shape measurements taken in such a manner can be related to the out of flatness measure of "I units" by a simple formula [16]:

$$\text{Shape} = \frac{H}{L} \times 100\% \ \text{steepness}$$

$$\text{I units} = \frac{\pi}{2} \times \frac{H^2}{L} . 10^5$$

where H = height of buckles

L = space between buckles

Off-line measuring techniques can be used to measure strip shape caused by both longitudinal stress patterns and through the thickness stress patterns. A variety of devices have been developed to accurately measure strip shape off-line.

These devices are useful both as a research aid, and as a device to corroborate and calibrate on-line measuring systems. The measuring techniques can be applied on-line where the strip being measured is not under tension, that is, when it exhibits manifest shape. The main devices at present are:

-The shapemaster R-100 [16], a device using contact LDVT's (Linear Displacement Voltage Transducers). (These become less accurate as strip gauge gets thinner)

-The Vollmer shapemeter table [17], which uses non-contact proximity transducers.

-The Laser flatness Table [18], which uses laser triangulation.

-The BNF (Fulmer Research) Shapemeter [19] which uses reflected light.

On-line measuring techniques can be used to measure strip shape caused by longitudinal stress patterns only.

In recent years a number of on-line shapemeters have been developed. All of the shapemeters use contact systems. The shapemeters measure the differences in stress at particular points across the strip width, these stress differences are related to strip shape. The main devices at present are:

-ASEA-BB Stessometer [20], continuous roll with transducers working on the magneto-elastic principle.

-Vollmer shapemeter [17], LDVT contact probes under pressure.

-Davy-Mckee Vidimon [21], segmented roll with Air Bearing Pressure measurements.

-Clecim-Plancim [22], continuous roll with LDVT's placed spirally around the roll.

-Broner Strainweb [23], segmented roll with strain gauges on a beam.

-Sundwig-Monitoring roll [24], segmented roll with piezo electric load transducers.

2.2 MODELLING OF SENDZIMIR MILLS FOR STRIP SHAPE CONTROL

Mathematical modelling is becoming increasingly important as a means to controlling strip shape. With the increasing power of computers, highly complex models can be run. Mill models can be static or dynamic. The complexity of models and the methods used in modelling are dependent on the end use of the model. Some models are used to control rolling parameters that affect strip shape. These model need to be fast acting, hence they are often simplified and large assumptions are made. Some models are used to investigate the behaviour of the rolling process, these models are complex, and increasingly finite element (FE) methods are being used.

FE models require a lot of computing power and accurate models take considerable amounts of time to run. This major drawback prohibits the use of such models as part of an integral on-line control system. The models can be used for research or to check other non-FE models.

The models can generally be split into two areas, the first aspect is that of roll force modelling and the second is that of total mill modelling.

Models of rolling are limited in that the behaviour of basic parameters such as the behaviour of the strip, the behaviour of the rolls and the lubrication are still poorly understood [25].

A Static model of a sendzimir mill has been produced by G.W.D.M. Gunawardene et al [26]. The model takes into account "roll bending" using beam and elastic foundation theory [27]. Roll flattening and inter-roll pressure is modelled using Timoshenko and Goodiers theories [28].

Roll force is calculated using Bryant and Osborns explicit roll force formula [29]. No firm conclusions have been drawn as to the ability of the model to aid in improving strip shape.

Takao Kawanami et al [30] dealt more accurately with the behaviour of strip, in that plane stain conditions were not assumed, ie a three dimensional stress analysis was carried out. Roll deformation was based on beam bending theory and use was made of finite element techniques. Roll flattening based on work by Tozawa [31] was employed.

The roll deformation of a Sendzimir mill was modelled by T. Matsucha et al [32]. The analysis was used to predict the best profile for rolls, which would enhance strip shape. The work is based on previous models which use a method of dividing rolls and strip into multi-portions [33]. Definite conclusions from this work are that:

a) Except for extremes of shape such as full centre of long edge then using the control parameter of first intermediate roll shift complex shape must be produced.

b) Using Saddle adjustments there is no condition in which good shape can be obtained, however, slight improvements can be made.

c) Work on improving strip shape must concentrate on roll profiles.

2.3 ROLLING PARAMETER EFFECTS ON STRIP SHAPE

On a Sendzimir 20 High rolling mill there are a large number of parameters which can affect strip shape. These are as follows;

a) Lubrication and cooling.

b) Rolling speed.

c) Rolling tensions.

d) Roll profiles.

e) Incoming strip profile.

f) First intermediate roll position.

g) Saddle settings.

h) Rolling load.

2.3.1 Lubrication and Cooling

Although the effects of lubrication and cooling are very different, they cannot be isolated from each other. Lubrication and cooling are vital in cold rolling to reduce the rolling load, ensure the strip finish is satisfactory, and remove the heat due to metal deformation. Mineral oils with additives are used in Sendzimir mills.

Improved lubrication reduces the rolling load. Many models have been forwarded which estimate the lubrication effects, but understanding is still limited. There are two types of lubrication thought to occur during rolling, "boundary" and "hydrodynamic" lubrication [34]. With a reduction in the rolling load required to deform the material being rolled, the mill bending characteristics change. The mill housing and rolls flex differently so altering the load distribution across the strip width.

Associated with this is a change in strip shape.

If there is non-uniform lubrication across the strip width, then there will be a non-uniform load distribution. There will also be differences in the speed of material passing through the roll bite.

These differences can significantly affect the rolled strip shape [35].

Non-uniform cooling will result in differential expansion of the mill rolls. This will give rise to loading differences across the strip width which results in strip shape changes. Temperature changes affect lubrication characteristics which in turn affects mill load and hence strip shape [36]. The heat transfer characteristics of a mill ensure that a thermal crown is built up on the rolls. That is, at the centre of the mill higher temperatures are built up which means that the rolls expand to form a barrel shape.

2.3.2 Rolling Speed.

Rolling speed directly affects the mill temperature build up and the lubrication. Nearly all of the energy supplied to a rolling mill is converted into thermal energy. The energy is dissipated in deformation of the strip and in friction effects. When looking at strip deformation the following factors need to be considered [37]:

a) Yield strength of the strip.

b) Strain rate during deformation.

c) Strain rate effect.

d) The sideways constraint to material flow.

Friction effects have been mentioned in "lubrication and cooling".

Mill temperature build up affects mill load, as does the lubrication effects. Mill load affects the bending of the mill which in turn affects strip shape.

2.3.3 Rolling Tensions

On modern Sendzimir mills extremely high rolling tensions are used. Tensions reduce the rolling load required for material deformation. Tensions also keep the strip running on line through the mill when the strip is too thin to be guided mechanically. A differential between the front and back tensions will affect the position of the neutral point, that is the point of no slip, which changes the frictional effects.

Rolling load is affected more by back tension, but strip shape is affected more by the front tension [39]. Sendzimir mill manufacturers recommend that rolling tensions of one third ultimate tensile strength (UTS) should be used.

There is a complex relationship between tensions and strip shape. When the mill load is affected the mill will bend in a different manner hance altering the strip shape. If the neutral point is affected, both the mill load, and the ironing effect of the rolls on strip shape change. The strain rate at different points in the roll gap is affected by the neutral point position, as is the lubrication.

Work has been carried out attempting to use tensions to control strip shape. A differential tension which affects the strip shape is created across the width of the strip.

The application of this technique assumes that plane strain conditions do not exist in the roll bite, but that lateral material flow takes place [40]. Various methods of creating a tension difference across the strip are used.

i) Localised heating of the strip.

ii) Cambering the pass line rolls.

iii) Applying differing load through segmented rollers.

Some evening out of stresses occurs at a distance from the mill roll bite. This phenomenon is known as the Saint-Venant principle [41]. This limits the effectiveness of these methods of shape control.

There is a theory that strip shape attenuation occurs when rolling under high tensions. Localised differences in tension occur across the strip width, caused by differential reduction of the strip. These tension differences affect the localised roll bite load, In an over rolled section of strip there is a reduction in tension and hence stress. The mill rolls experience an increase in rolling load which is translated into an increased roll deformation. Increased roll deformation means that less localised over rolling occurs on the strip, and strip shape attenuation has occurred [42].

2.3.4 Roll Profiles.

A large amount of work concerned with roll profile has been carried out an 4 and 6 high mills, but little progress has been made on cluster mills. The, as ground, roll profiles have a significant part to play in matching the incoming strip profile to the roll gap profile. In a cluster mill the following rolls can be profiled (Figure 3);

i) Work rolls.

ii) First intermediate axially adjustable rolls.

iii) Second intermediate rolls.

The further set of rolls are Castor Bearings which can be independently adjusted via saddles to give strip shape control.

Experience plays the major part in deciding which roll profiles should be employed. The type of material rolled, the reduction given, the mill, and the rolling staff, all contribute to the choice of roll profile.
Work rolls are generally ground flat or cambered, although they can be ground concave.

The first intermediate axially adjustable rolls have a Taper ground over a portion of their length. The length of taper is dictated by the width of material rolled. Taper angle is dictated by the material type, mill characteristics, and experience.

Some recent work has been carried out on trying to optimise the first intermediate roll profile. Mill manufacturers "Sundwig" recommend that a curve is ground on the roll rather than a straight taper.

Recent work [32] suggests that a double taper on the roll end will help to produce better strip shape. The shape defect of quarter buckle should be reduced with this roll profile.

The second intermediate roll's profile is again dependant on the material rolled, the specific mill, and experience. Either flat (parallel), ground rolls or cambered are used.

2.3.5 Incoming Strip Profile.

The effects of incoming strip profile on finished strip shape can be broken down into two areas:

i) The supplied strip profile and whether this determines the finished strip shape.

ii) The intermediate rolled strip profile and whether the profile can be changed significantly during rolling.

There is no published work which proves the relationship between the incoming strip profile and final strip shape. There is work which suggests that the final strip shape is not as severe as can be calculated from the differential in percentage reduction across the strip [43]. Bernsman suggests that lateral material flow takes place in the roll gap, which reduces significantly the effects of incoming strip profile on final strip shape. The assumption that plane strain rolling conditions exist are questioned. If plane strain conditions do not exist during cold rolling, then much of the work on strip shape which is based on differential percentage reductions is not valid.

In order to effect automatic control of strip shape based on differential percentage reductions, the incoming strip profile needs to be described. Hot rolled strip usually has a slightly convex cross-sectional profile.

The size of crown allowed is dealt with in regulations [44]. Strip can be supplied in a variety of profiles. Flat, wedge, concave, and offset crown profiles are known. for narrow mills hot roll wide coils need to be split into three or four sections. If the wide parent coil has a convex profile then the small coils will exhibit wedge and convex profiles.

The incoming strip profile is described for computational purposes in the form of a polynomial equation [45]

$$h_{(z)} = h_m + K_1Z^2 + K_2Z^3$$

where h_m = centreline thickness

K_1,K_2 = constants

h_z = thickness of the strip at a set distance from the centreline

2.3.6 First Intermediate Roll Position.

On a Sendzimir cluster mill the first intermediate rolls (Figure 3) are axially adjustable. The rolls have a profile ground on them and adjustment of the roll positions enables the mill operator to control the strip shape, and the strip line.

The first intermediate roll position is closely linked to its geometry in its effect on strip shape. The first intermediate roll position is the most powerful means of strip shape control on a narrow cluster mill [43].

Rolling thin gauge material means that the strip cannot be held centrally in the mill by guides. Guides would damage the strip edge and cause strip breaks. The only means available for keeping the strip on line (running centrally) are tensions, saddle adjustments, paper interleaving (paper builds a crown on the coils which centralises the strip), and first intermediate roll positions. Rolling tensions are normally high so little can be done to help steer the strip other than normal rolling practice. The mill loading pattern can be altered by adjusting the saddles. This adjustment will help in steering the strip but its effect is limited.

Inserting narrow paper into the coil as it is building up helps to keep the strip on line. Using the first intermediate roll position to hold the strip on line is the major means available. The drawback to using the first intermediate rolls to control strip steer is that they also control strip shape. Often a compromise position must be accepted.

The most advanced feedback automatic strip shape control systems utilise the first intermediate roll positions. Movement of the roll positions are limited because of the risk of causing strip breakages.

2.3.7 Saddle Settings.

The individual casters (back up bearings), (Figure 3), can be adjusted on a Sendzimir mill to give a change in the mill loading pattern. Each saddle, which transmits the rolling force to the mill housing, can be adjusted. This alters the mill loading. The saddles are eccentric so that by turning screws located in them the saddle is rotated slightly in its housing. This alters the inclination and relative positions of the Castor (back up bearing). Primarily, the saddles were designed to enable control over strip steerage. Now that strip shape is of greater concern, saddle adjustments are used to give some degree of strip shape control.

Modern mills incorporate hydraulic or electro-mechanical means of saddle adjustments. Older mills are often retro-fitted with similar means of saddle adjustments.

There is conflicting evidence at present over the success of improving strip shape via saddle adjustment alone [47,48,32].

Some researchers claim that they have only a slight effect on strip shape, others that the major benefits of controlling saddles have been increased productivity and others that they are controlling shape successfully.

The measure of success is usually that control of shape is better than that effected manually. There is little published evidence that proves real strip shape improvements. strip shape control using saddle adjustments will be more effective on wide mills than narrow mills.

2.3.8 Rolling Load.

Mill load affects a large number of rolling variables. These are the variables affected:

i) The behaviour of the material will alter with load differences. That is, the strain rate, and phase transformations can alter.

ii) The lubrication conditions alter. With changes in lubrication there will be a change in the position of the neutral point.

iii) The thermal conditions change. Higher rolling loads will increase temperatures due to the increased strain rate. The cooling may be less effective due to oil vaporisation.

iv) Mill bending changes. The roll cluster and mill housing will curve in a concave manner.

v) Roll flattening changes. All of the rolls flatten to some extent. With increased mill load then more roll flattening will occur.

Each of the itemised variables effected will cause strip shape changes. It is clear that rolling load plays an important part in its affects on strip shape.

2.4 EXPERIMENTAL DESIGN USING TAGUCHI EXPERIMENTAL DESIGN TECHNIQUES.

Due to the large number of rolling variables and their interactive effects, statistical techniques of experimental design were researched and used. The techniques employed were "Taguchi Experimental Design Techniques" [49,50]. Taguchi popularised the use of experiment design for engineers. He put statistical methods in engineers language. The emphasis of the experimental procedure is on parameter design, and not tolerance design. That is, adjusting the product parameters or process factor levels such that the product is optimised with minimum sensitivity to "noise", "noise" being the sensitivity of the optimum product attributes to variations. Whereas, tolerance design means spending money on better materials etc..

Emphasis is placed on the planning stage of the experimental procedure (Figure 4). The size of the overall experiment is reduced by choosing to neglect some interactions. Experiments are designed using balanced arrays which dictate the settings for process variables and linear graphs which enable interactive effects to be allocated. After the design and set up of the experiment controlled execution is carried out. The results can be analyzed in a number of ways. Most relevant information is obtained by looking at the mean response graphs [4,49]. A method used to confirm the significance of the results is an analysis of variance [4]. More complex analyses are available [50] but were not appropriate for this project.

The Taguchi Philosophy means that observation is taken of the process variability. This is analyzed by looking at the signal to noise ratio. A strong signal and weak noise means that the process is robust ie, not subject to variability [4].

2.5 WORK ROLL STRAIN

Strain measurement is used to find the bending characteristics of a loaded work roll. The bending of work rolls is related to specific strip shape defects. By observing the severity of work roll bending due to changes in rolling parameters, the different magnitudes of effects and characteristics of effects of such parameters can be examined. No previous experimental work has been referenced in this area.
Theories about roll flattening and bending have been made [51].

According to Fappols formula, mutual flattening of a pair of mating rolls is proportional to the contact load over the working range.

Flattening in given by the displacement of the roll axis in the direction of contact. Experimental evidence [52] reveals a close connection between the calculated and real displacements. Models are available which predict roll bending. These generally use Elastic Foundation Theory [28]. Finite Element (FE) work can predict roll flattening and bending but it is difficult to corroborate the results. Corroboration can be carried out by testing the ability of the model to predict shape, roll force and torque etc. This corroboration has not been carried out conclusively.
To understand the behaviour of work rolls their strain can be measured directly. the limitation of this is that because of the harsh and dynamic environment strain measurements can only be measured with the mill static (ie, not rolling).

Strain can be measured using a variety of techniques but the most robust and reliable is that of using strain gauges.

Techniques for strain measurement have been used for a long time and are well established. Strain gauges alter in resistance when they are extended or compressed. The value of strain can be related to stress. Directions of principle strains can be found if required. Gauges are robust and sensitive and can be used to accurately measure very small changes in strain. Measurements of strain can be made by Wheatstone bridge balancing units but now more commonly by electronic means.

The rolls of which the bending characteristics were measured are work roll in contact with the strip during rolling. Their dimensions vary between 48.26mm (1.9") to 43.18mm (1.7").

The rolls are 2%C 12%Cr die steel

hardness 62 Rockwell C.

3.0 APPLICATION OF TAGUCHI TECHNIQUES TO DESIGN OF EXPERIMENTS

The experimental work followed a logical sequence and the steps taken are shown in Figure 4.

Although the objectives of the programme were clear the experimental work was results driven in the sense that data acquisition determined the next step. A number of experimental objectives related to strip flatness followed, some required large programmes of work but others smaller programmes. The major areas are considered first.

4.0 APPLICATIONS OF STATISTICAL EXPERIMENTAL DESIGN TECHNIQUES TO A SINGLE PART OF A ROLLING SEQUENCE.

4.1 INTRODUCTION

The cold rolling process involves a large number of variables (Table 1) which can affect the final strip shape. It was not feasible to exaustively test each variable because of the cost considerations and the difficulty of producing the same specification of strip for fixed rolling conditions.

The complexity of the rolling process means that, to affect adequate control over strip shape, an intimate knowledge of the combined and individual effects of all of the rolling variables is necessary. Experimental design techniques known as "Taguchi" techniques were employed:

-To find the major strip shape affecting variables

-To optimise the controllable process variables (parameters) which give the best strip shape.

4.2 PLANNING AND DESIGN

To keep the rolling experiments to an acceptable number of coils which could be tried , and to build in experimental consistency the following were kept constant:

a) Lubrication -temperature

-spray pattern

-specifications

b) Strip thickness and width

c) Two sister coils were used to eliminate slight material differences (these were assumed to have negligible effect on strip shape within material qualities).

d) The mill roll sizes.

e) The mill rolling team. Differences due to experience or operating practices were eliminated.

The number of parameters was reduced to ten, shown in Table 2. It was considered that four of the parameters interacted.

The number of parameters and interactions dictates the size of the experiment. Following recommended procedures to apply Taguchi techniques an experimental plan of sixteen test runs was required. The plans are known as orthogonal arrays. The array required was an L16 [4].

Parameters and interactions are assigned to columns in the experiment plan. Use is made of linear graphs to assign the assumed interactions to their appropriate columns.

Experiments were carried out on one full working shift. Rolling reductions, speeds, tensions etc. were kept constant through all the preceding processes.

Strip shape samples were taken from steady state rolling conditions.

The experimental techniques handle a limited number of parameter settings. The number of settings can be chosen and the experiment designed to take account of them.
More settings mean more tests, and hence a much larger experiment. Since the aims of this experiment are broad then two settings or levels of each parameter were used. The actual levels are shown in Table 2.

4.3 CRITIQUE OF THE EXPERIMENTS

The nature of the rolling process meant that certain of the parameter settings could not be chosen prior to the strip being placed on the mill. If there was any combination of settings that would not allow "safe" rolling the whole set of tests would be wasted. All sixteen of the tests needed to be carried out, if any test was not completed then the analysis of results would be incomplete. This is due to the statistical balance of the array.
Between the two coils used for the tests there was a slight width difference which could not be avoided.

No accurate measure could be taken of the previous strip shape because the tests had to be carried out on a specific rolling pass.
The range of parameter setting chosen is important. There is difficulty in assessing what differences to use but ranges and setting were chosen to be compatible with normal operating conditions. Some parameters were considered to be less significant and were not taken into account. These were as follows;

a) Process route of the coil.

b) Differences in material composition or profile throughout the length of a coil.

c) Thermal effects (although held constant as far as possible).

d) The accuracy of the mill settings.

e) Work rolls needed changing occasionally and so there were slight differences in diameters.

4.4 RESULTS

The strip shape samples were measured in three different ways. A scale of 1-10 was given for visual shape appearance. A score of 10 was awarded for extremely poor shape and 1 for good shape.This measurement did not take account of any specific strip shape defect. The results are shown in Table 3.

A scale of 1-4 was given for specific strip shape defects. A score of 4 represented poor strip shape and 1 good shape. The defects were edge wave, full centre, ripple (herringbone), quarter buckle and coilset. The results are shown in Table 4 a-d.

A measurement of the difference in gauge profile across the strip was taken. The results are shown in Table 5. The lowest value given indicates the best strip shape.

Mean response plots [4,49] are used to illustrate the effect of each parameter for each method of measuring shape. The mean response plot is the average response of strip shape to the parameter under investigation. Lowest mean response indicates the best strip shape.

To obtain the mean response for each parameter the average results at each parameter level was obtained. These average results are plotted for each level. The severity of the slope of the graph indicates the extent to which a parameter affects the measured variable (strip shape).

The interaction plots show how the specified parameters affect each other. Parallel plots indicate that no interaction exists. Non-parallel plots indicates that there is an interaction. The severity of interaction is given by the amount that the lines are out of parallel. There can be positive and negative interactions. A positive interaction occurs when the interactions combine to improve the measured variable and vice-versa.

To confirm the significance of the results and their spread required analysis of the variance [4].

A wide spread of the results would mean that the slope of the graph could vary dramatically and therefore confidence in the results would be low.
To carry out an "analysis of variance" the variations of each parameter were found. The least significant parameters are then pooled. These parameters were those having a low sum of squares value [4]. The pooled parameters give a value called the error mean square (EMS). The values which have not been pooled are divided by their specific degrees of freedom, this gives a result termed the mean square (MS). The MS values are divided by the EMS to give a value of significance.
Statistical confidence Tables published by "Fisher" known as "F" Tables, give values for different percentage confidences based on the degrees of freedom of the numerator and denominator.

If the MS divided by the EMS values are higher than the numbers obtained from the "F" Table, then the specified percentage confidence shown in the results is attributed to the result.

4.5 ANALYSIS

Inspection of the mean response results and the analysis of variance enables parameters to be placed in order of significance. That is, the level of effect that each one has on strip shape. Taking each strip shape measuring method, parameters have been placed in order of magnitude. Comments are made as to how the results compare to rolling experience. This experience is based on interviews with rolling staff.

4.5.1 Edge Wave.

The mean response plots and results for edge wave are shown in Figure 5 a-c. Significant parameters which are obtained from the mean response plots are shown in order:

a) First intermediate roll position.

b) Work roll geometry.

c) Strip geometry and first intermediate roll position interaction.

d) Strip geometry.

e) First intermediate roll position and strip geometry interaction.

f) Work roll size difference.

g) Front tension.

These results were confirmed by knowledge of rolling experience:

The first intermediate rolls positions, the most significant parameter, is the key to affecting strip shape. Moving the first intermediate rolls so that there is less taper covering the strip (flat) means that edge wave is created. Rolling with flat work rolls gives more likelihood of producing edge wave.

Findings which are new:

a) Strip geometry, although important, is not the key shape affecting or controlling parameter.

b) Wedge strip and shallow tapered first intermediate rolls are the preferred combination in that if the use of wedge strip is unavoidable then use shallow tapers.

c) Flat strip and steeper tapered first intermediate roll are the preferred combination in that if rolling flat strip then use steep tapers.

d) Keeping the work rolls the same size reduces the amount of edge wave.

e) Front tension has more effect on strip shape than back tension [56].

4.5.2 Full Centre.

The mean response plots and results for full centre are shown in Figure 6 a-c.

Significant parameters in order of significance are:

a) First intermediate roll position.

b) Work roll geometry.

c) First intermediate roll geometry and strip geometry interaction.

d) Reduction.

e) Strip geometry.

f) First intermediate roll position and strip geometry interaction.

These findings were confirmed by rolling experience:

The first intermediate roll position is the key strip shape affecting parameter. Rolling with less flat on the strip causes "full centre" to be rolled.

The work roll geometry is important in the production of strip shape. Cambered rolls encourage full centre strip shape.

The amount of reduction alters the amount of full centre.

New findings:

a) for wedge strip, shallower tapers are preferred. For flat strip steep tapers are preferred.

b) Strip geometry does not play a major part in producing strip shape.

c) Within the small changes of first intermediate roll geometry tried, there are only minor strip shape effects.

4.5.3 Ripple (Herringbone).

The mean response plots and results are shown in Figure 7 a-c.

Significant parameters in order of significance:

a) First intermediate roll position.

b) Front tension.

c) Reduction.

d) First intermediate roll geometry.

e) Work roll size.

f) Back up roll (saddle) configuration.

These findings are confirmed by rolling experience:

The first intermediate roll position is the key strip shape affecting parameter.

Increasing the front tension will reduce the amount of ripple.

Increasing the rolling load reduces ripple.

New findings:

a) A shallow first intermediate roll taper will reduce ripple.

b) Keeping the work rolls the same size will reduce ripple.

c) The mill loading pattern from the saddle setting will affect the creation of ripple.

4.5.4 Quarter Buckle.

The mean response plots and results are shown in Figure 8 a-c.

Significant parameters in order of significance:

a) Work roll geometry.

b) First intermediate roll geometry.

c) Speed.

d) Back up roll (saddle) configuration.

New findings:

Roll geometries are key quarter buckle affecting parameters. To remove quarter buckle the roll geometries must be altered.

Work roll geometry differences tested were more severe than the first intermediate roll geometry differences.

This accounts for the work roll geometry being more significant.

Rolling speed which affects load, lubrication, neutral point and temperature is seen to affect quarter buckle.

4.5.5 Visual Representation.

The mean response plots and results are shown in Figure 9 a-c.

Significant parameters in order of significance:

a) First intermediate roll position.

b) Strip geometry and first intermediate roll geometry interaction.

c) Work roll size.

d) Reduction and back tension interaction.

e) Speed.

f) Reduction.

g) Reduction and work roll size interaction.

h) First intermediate roll and strip geometry interaction.

i) Front tension.

The visual assessments do not differentiate between shape defects. This means that parameters which are significant to individual shape defects, are also significant to this method of shape measuring. When comparing the significance of parameters, the visual assessment results are similar to the full centre results.

These findings are confirmed by rolling experience:

a) The first intermediate roll position is the key strip shape affecting parameter.

b) There are many parameters that affect the visual appearance of strip shape. An intimate knowledge of the rolling process is necessary to effect control of strip shape.

New findings:

a) Different first intermediate roll geometries should be used with different strip geometries.

b) Improvements can be made to strip shape if the work rolls are kept the same size.

4.5.6 Profile differences.

The mean response plots and results are shown in Figure 10.

Significant parameters in order of significance:

a) Strip geometry.

b) Speed.

c) Front tension and reduction interaction.

d) First intermediate roll position.

e) Work roll size.

f) Back up roll configuration.

The incoming strip profile strongly affects the differences in profile after rolling. Rolling speed affects the profile difference. This may be due to the lubrication, loading and thermal changes encountered. Speed may also affect lateral material flow during rolling. The importance of the front tension and reduction interaction may be related to rolling load and hence speed of rolling.

As expected the first intermediate roll position affects the strip profile.

Work roll size differences and back up roll (saddle) positions show small measurable effect on strip profile.

5.0 INVESTIGATION INTO THE EFFECTS OF DIFFERENT WORK ROLL PARAMETERS ON STRIP SHAPE.

5.1 INTRODUCTION.

The specific aims of this work were:

a) To confirm that keeping work rolls the same size helps to improve strip shape.

b) To confirm that keeping work roll diameters small on the specific mill helps to improve strip shape.

c) To identify, in more detail, the extent to which work rolls affect strip shape.

During the planning stage of the experiment, a close look was taken at the parameters which could affect "coilset", "cross-camber" and "full centre" strip shape defects. The reason for this was that measurements had shown that these defects occur at the same time. This implies that these defects may be caused by the same factors. If any one of these defects can be removed then the others may also be eliminated.

Taguchi Experimental Design Techniques [4] were employed for this area of work. Tests were carried out on a single coil to ensure consistency of material proportions and geometry. For the trials the coil was run up to speed and held at steady state conditions. The sample was marked then the mill stopped. Rolling parameters were then adjusted and the mill run to steady state conditions for the next sample.

The parameters that were tested are shown with their settings in Table 6.
For completeness it would be better to use a more extensive range or work roll geometries and combinations but this was not practicable. Reasons for not doing so were:

a) A vast number of work rolls would be required for the tests.

b) Confusion would occur in handling the number of rolls.

c) The experiment size would increase dramatically.

d) Individual experiments focused on the best work roll geometries for specific jobs would prove more useful.

5.2 DESIGN OF EXPERIMENTS.

There are six parameters under investigation, Table 6. All of the parameters are held at two levels. The smallest "Taguchi" orthogonal array which can be used is the L_8. No allowance was made for interactions, there are two reasons for this:

a) The method of measuring results was not considered accurate or detailed enough to assess small interactions.

b) Minor interactions were thought to be of little use to the experiment aims.

Although at the design stage of the experiment no interactions were allowed for, because of the practicalities of the experiment, one interaction was allowed. During the trials it was found that the pass line height, as planned, could not be altered.

The column of the array assigned to the pass line height will pick up on interactions.

As far as possible all variables except those under investigation were held constant. Steady state rolling conditions were achieved for each strip shape sample.

5.3 RESULTS.

There are four methods chosen for measuring the results, these are as follows:

a) the shape defect of "full centre" was given a value between 1-4 dependent upon the severity of the shape defect encountered. The lowest value indicates the best shape.

b) The shape defect of "loose edge" was given a value between 1-4 dependant upon the severity of the shape defect encountered. The lowest value indicates the best shape.

c) A scale of 1-10 was used for visual appearance. No differentiation was made between shape defects with this measurement. The lowest value indicates the best shape.

d) A measure of the profile difference across the strip was recorded. It is likely that the greater the difference in strip profile, the worst are the rolling conditions with reference to strip shape.

5.4 ANALYSIS.

5.4.1 Edge Wave (Loose Edge).

The mean response plots and results are shown in Figure 11. Significant parameters are listed below:

a) Roll geometry.

There are indications of improvements with the other parameters tested, but their level of significance is very low.

5.4.2 Full Centre.

The mean response plots and results are shown in Figure 12.
Significant parameters are listed below:

a) Roll geometry.

Again there are indications that improvements can be made with other parameters tested but their levels of significance are low.

5.4.3 Visual Scaling.

The mean response plots and results are shown in Figure 13.
Significant parameters are listed below:

a) Roll geometry.

b) Roll size and roll configuration interaction.

The major parameter is the roll geometry. There is a negative interaction between the roll size and configuration. Trends can be interpreted from the other parameter results but they are of low significance.

5.4.4 Profile Difference.

The mean response plots and results are shown in Figure 14.

Significant parameters are listed below:

a) Roll size and roll configuration interaction.

b) Roll configuration.

A negative interaction is shown between the roll size and the roll configuration. Roll configuration plays the dominant part in the interaction. Having different roll sizes affects the level of profile difference of the strip. All of the other parameters are of low significance.

5.5 DISCUSSION.

5.5.1 General Discussion.

It is clear from the results that the work roll geometry is, out of those parameters tested, major in its effect on shape. There are indications from the mean response plots that improvements can be made by:

- using small work rolls.
- keeping the work rolls the same size.
- keeping the tensions high.

Actions, dictated by this work, which can help to reduce strip shape defects are included in Appendix 1.

6.0 INVESTIGATION INTO THE EFFECT OF SADDLE (MILL LOAD PATTERN) ADJUSTMENTS ON STRIP SHAPE.

6.1 INTRODUCTION.

The work carried out in this project indicates that saddle adjustments have little effect on strip shape. Industrywide, there has been significant investment in utilizing saddle adjustments to effect shape control. This is in the form of closed loop automatic feedback control systems. Both to confirm that the saddles have a small effect on strip shape, and to give guidance for investment, a detailed analysis was required of the affects of saddles on strip shape.

The investigation had three stages:

a) Assessing the effects of saddle adjustments on strip shape over short lengths of strip.

b) Assessing the effects of saddle adjustments on strip shape over a finishing pass.

c) Assessing the effects of saddle adjustments on strip shape over a complete rolling sequence.

6.1.1 Optical Shapemeter.

The off-line shapemeter as developed by Fulmer Materials Technology, formerly B.N.F.(Metals), it was found to be an accurate method of measuring strip shape.

Strip shape was measured by comparing the actual length of measured strip with the length of a flat piece of strip. The shape calculation could then be carried out, that is:

$$\frac{\Delta L}{L} \times 10^{-4} = \text{Strip shape "mons"}$$

L = length measured- length of flat strip portion

ΔL = length of flat strip portion.

The method used to ascertain the strip length is as follows. A sample of strip to be measured was attached to a frame and sufficient tension applied to remove the defect of coilset, cross camber and twist was applied. That is, the shapes caused by through the strip thickness stress patterns. The tension applied could be recorded, hence it could be held static for measuring a series of similar samples. At a set point on the strip a beam of light was focused. The strip was then moved under the light at constant velocity. The light was reflected off the strip with an angle dependant on the shape of the strip, Figure 15. As the strip moved under the beam the angle change is integrated to give a measure of the length of strip. A trigger mechanism indicates the start and end of measuring, so the length of strip and the length of a flat piece of strip is known and the shape can be calculated. Measurements are taken at pre-determined points on the strips width so a picture of the overall shape can be obtained.

Measurements of strip shape were accurately carried out using an off-line optical shape meter, Figure 15. The shapemeter was developed by Fulmer Materials Technology, formerly B.N.F.(metal) technology.

6.2 DESIGN OF EXPERIMENT.

6.2.1 Altering Saddles Over Short Test Runs.

Initial assessments of the effects of saddle adjustments were made on short lengths of strip. The tests were carried out on the last pass of a rolling sequence. A variety of saddle setting were tried, with all other rolling parameters being held constant. Three sets of tests were carried out on three individual coils.

The saddle settings chosen, and which are shown on the strip shape plots, give all the major loading pattern differences. The saddle adjusting screws can be altered between positions 0-10, with mill designers recommending that no more than 1.5 units difference should be used between adjacent adjusters. Tests on two of the coils were carried out using 2 units difference between adjacent saddle settings (Figure 16). Since no major strip shape change was recorded the adjacent saddles were set with 3 units difference.

6.2.2 Setting the Saddle Configuration Over a Complete Rolling Pass.

This technique was used to ensure that steady state rolling conditions were achieved for the measured samples. The effects of setting the saddles for a complete pass in a rolling sequence were thereby assessed.

The trial was designed so that all of the non-tested rolling parameters were kept constant as far as possible for the tests. Two tests were carried out, one large coil was rolled down to the last pass, then split, and the tests carried out. The only difference in the rolling parameters was that of the saddle configuration.

The test samples were obtained from the mid-point of each coil, this ensured that the sample was representative of the main body of the coil. A differential of 3 units was held between adjacent saddle settings. Two extremes of loading pattern were used (Figure 17).

6.2.3 Altering Saddles Through a Complete Rolling Sequence.

Investigating the effects of altering parameters throughout a rolling sequence will show whether early process changes affect strip shape. Work practice is to take strip shape into account only on the last or last two rolling passes.

Taguchi experimental design techniques have been used to quantify the effects of saddle adjustments through a sequence. Work (see ch.4.5) has shown that the work roll geometry is more significant than the saddle settings on a single rolling pass. To gain a comparison of effects, it was decided that the experiment should incorporate both the saddle configurations, and the work roll geometry. Table 7 shows the settings of the parameters chosen. The orthogonal array used on which to design the tests was an L_4 [4]. Four tests were required to complete the experiment. Two large sister coils were split to produce the four coils necessary. The coils were rolled in a similar manner, the only difference being those dictated by the experiment plan. The positions of saddle setting chosen were to encourage two extremes of mill loading pattern. One setting would load the mill more at the centre, and the other more at the edges, Figure 17 a-b. That is, convex and concave loading patterns were used. Setting of 2 units difference between adjacent adjusters were used. Two extremes of work roll geometry were chosen for the tests. That is, either two flat or two cambered work rolls.

6.3 RESULTS

6.3.1 Altering Saddles Over Short Test Runs.

Between the three coils tested there are large differences in strip shape. These differences cannot be related to the different saddle adjustments so must be due to more dominant rolling parameters such as the relative position of strip and first intermediate rolls etc. There is no obvious link between the loading pattern across the mill, caused by saddle alterations, and the small shape differences recorded. The three coils exhibit three typical strip shape defects, these are:

a) Loose edge.

b) Good shape.

c) Quarter buckle.

6.3.2 Altering the Saddle Configuration over a Complete Rolling Pass (Figure 17b).

Two major alterations in saddle settings have produced very little difference to the strip shape. The strip exhibits a slight quarter buckle at one side and loose edges. This is a typical shape defect for the mill under investigation.

6.3.3 Altering the Saddles Throughout a Complete Rolling Sequence (Figure 18).

From the strip shape plots it can be seen that there is a significant difference between the samples. The differences are caused by changes in work roll geometry and saddle adjustments. Two of the plots 1-2, show a full centre strip shape. The other two plots 3-4, show a loose edge. Plot 3 also exhibits a quarter buckle.

To analyze the results statistically, two methods of describing strip shape are used. One method was a visual judgment, the value of 4 was awarded for the worst shape and 1 for the best. The second method was to average the shape measurements.

From the results mean response values were calculated and plotted (Figure 19). An analysis of variance was carried out to confirm the significance of the results. The steepest mean response results are for the work roll geometry. This means that the work roll geometry has greater effect on strip shape than saddle adjustments. There is an effect on strip shape shown to be caused by the saddle settings. The analysis of variance confirm that these observations are significant. One column of the array was assigned to an interaction but no interaction is shown. the work roll geometry and saddle adjustments have been found to affect strip shape independently.

7.0 EFFECTS OF ROLLING PARAMETERS ON STRIP SHAPE THOUGH A ROLLING SEQUENCE

7.1 INTRODUCTION.

Work presented in section 4.5 shows the effects of mill rolling parameters on strip shape. The work was limited, in that tests were carried out on a single pass of a rolling sequence. Certain rolling parameters may have an unmeasurable effect on a single rolling pass, but throughout the rolling sequence the effect can be significant. The effects of parameters on strip shape can be cumulative, as shown in section 6.3.2. This work investigates the effects on strip shape of rolling parameters throughout a rolling sequence.

Tests were carried out on type 316 austenitic stainless steel. Start and finish gauges were 1.22mm to 0.305mm, 75% reduction. The strip was 312mm wide.

Based on knowledge of the most significant strip shape affecting parameter already found, this work aims to find the cumulative effects of these parameters. This work aims to give guidance as to the best setting at which to hold the rolling parameters to give good consistent strip shape. Use is made of "Taguchi" experimental design techniques. Attempts are made to reduce the process variability by an analysis of the signal to noise ratio (S/N) [4, 50,56].

7.2 EXPERIMENTAL TECHNIQUE

The total number of tests in an experiment is dictated by the number of parameters under investigation, the number of different settings (levels) of each parameter, and the number of assumed interactions between parameters. Limitations of production meant that the number of tests had to be reduced to a minimum.

Certain parameters have been held constant to reduce the experiment size. These are:

a) Material quality (grade 316)

b) Physical properties: -width 312mm

-start thickness 1.22mm

-final thickness 0.305mm

-profile constant

The parameters chosen for investigation and their levels are shown in Table 8. Three parameters were chosen for a more detailed analysis. This was because it was hoped that guidance about rolling practice would be gained from the results, not just the significance of parameters. These were held at three levels. All of the other parameters were held at two levels.

Certain of the parameters could be isolated in that it was known that their effect throughout the rolling sequence was measurable. The parameters to be isolated were:

a) The first intermediate roll position.

The procedure was to aim for a specified strip shape throughout the rolling sequence and then aim to produce good flat strip shape on the last pass. The best target shape prior to the last pass could therefore be found.

b) The mill loading patterns (saddle settings).

Previous work has shown that the saddle setting have negligible effect on the last pass (or a single pass) of a rolling sequence. If they show any measurable effect then it must be entirely due to the sequence.

c) The reductions.

High reductions on individual passes mean higher rolling load on less passes to achieve the final gauge. As there has been no change in the reduction on the last pass, all noted differences in strip shape must be due to the alterations in the severity in rolling prior to the last pass.

Apart from the parameters above, all of the other parameter affect the strip shape throughout the rolling sequence and on the last pass. Therefore, the effects of the parameters cannot be isolated from the last pass, although it is known that they do contribute to cumulative effects on strip shape.

7.3 RESULTS.

Three methods were used in analyzing the results, these are:

a) By analyzing the mean response graphs. The severity of effect of each parameter is shown by the steepness of the slope.

b) Analysis of variance. (A.N.O.V.A.). This confirms the significance of the mean response findings.

c) Signal to noise ratio, (S/N). This enables the factors to be highlighted which effect the variability of the process. The ideal situation is where the process variability can be reduced at the same time as the strip shape [55].

After each rolling trial, which consisted of rolling a complete coil at the settings dictated, samples were collected from the centre of the coil. This ensured that strip shape samples were collected at steady state rolling conditions. The samples were representative of the major part of the coil. Shape measurements (obtained from optical shapemeters) were taken at seven points across the width of the strip. The units of measurement being mons [6-10]. The shape plots are shown in Figure 20 .

Three methods of describing strip shape were used, these are as follows:

a) Full centre. Here the highest recorded measurement of strip shape across the middle of the strip was used. No account was taken of strip shape near to the edges. The mean response plots for this measure are shown in Figure 21 .

b) Average strip shape. The fine centre shape measurement values were averaged. The two outer shape values were not used due to the edge measurements being the least reliable. Values of these shape measurements are shown in Figure 22 .

c) Loose edge. The four outer edge shape measurements were averaged for these results, using two measurements from each side of the strip. There is a complete set of mean response plots shown in Figures 23 for the loose edge results. When analyzing the plots, the lowest mean response relates to the best strip shape.

A synopsis of all the results must be taken when drawing conclusions about rolling practices.

The Analysis of Variance for each of the methods of shape measurement are shown in Table 9.

7.4 CRITIQUE OF THE EXPERIMENT.

The experimental work concentrated on one particular type of material, size and reduction. Additional work would be needed to confirm whether the findings are transferrable to other strip outside this specification. Considerable attention has been given to ensure that the most significant variables affecting strip shape had been included in the experiment. Previous work has directed the variables to be considered, but the rolling process is still not consistent. Although unlikely there may be variables and interactions affecting strip shape which have bot been considered. The limitations of production and resources meant that more exhaustive tests could not be carried out. The tests depended to some extent on the rolling mill operators, care had to be taken to ensure rolling operators were consistent, however, operators may not be consistent between tests. Moods can vary and attitudes which will affect the way in which the strip is rolled.

Work assumes that the rolling variables have a cumulative effect throughout the complete rolling sequence. It may be that the only place where the variables affect strip shape are on the last two or three rolling passes of a sequence.

7.5 ANALYSIS.

When analyzing the results to find the best parameter settings to optimise strip shape their effects should be looked at both individually, then as a whole. When taking a synoptic view of the results, some assessment of the reliability of each individual set of results must be given.

This relates to the reliability of the measurements concerned with average shape, full centre, loose edge, and variance (S/N). Reliability was checked by duplicating some of the parameter settings, then making certain that the results matched.

During the experiments two parameters were set at three levels as referred to in section 4.2. The orthogonal array used to design the experiment allowed four levels to be used. Each of these two parameters had one of their levels duplicated. Where the settings were duplicated the mean response plots should show similar values. Similarities in the results suggests confidence in the results.

The parameters used for duplication were:

A) Work roll profile.

B) First intermediate roll position.

From the mean response plots of parameter "A" (Figures 21-23) the response at level 1 should equal that at level 4. From the mean response plots of parameter "B" the response at level 3 should equal that at level 4.

The loose edge mean response plots (Figure 23) reveal discrepancies between the two levels. However, the trend of the results are similar.

The variance mean response plots (Figure 24) reveal some discrepancies between the two levels. Both of the remaining sets of plots, those for full centre and average shape, show similar mean response values for the two levels.

The measures of loose edge and process variance are the least reliable, whilst the measures of average shape and centre fullness are the most reliable.

Reasons why the loose edge method of shape measurement might not be reliable are:

- The absolute positioning of the strip with respect to the shapemeter head may be different between samples.
- The measure of loose edge is more sensitive than full centre.
- Whilst rolling, any lateral movement of the strip across the mill will cause edge shape problems.

7.5.1 Major Strip Shape Affecting Parameters (by Measuring Methods).

Full centre strip shape:-

The mean response results plots are shown in Figure 21.

Significant parameters, in order of significance are:

a) First intermediate roll position.

b) Work roll profile.

c) Saddle setting.

d) Tensions.

e) Reductions.

f) Speed.

The saddle setting are shown to have a large effect by the mean response graphs, but the analysis of variance shows that there is low confidence in the results.

Average strip shape:-

The mean response results plots are shown in Figure 22.

Significant parameters, in order of significance are:

a) First intermediate roll position.

b) Work roll profile.

c) Rolling mill operators.

Other parameters show trends which can be used as guides to improve shape, but levels of confidence in the results are low.

Loose edge:-

The mean response results plots are shown in Figure 23.

Significant parameters in order of significance are:

a) First intermediate roll position.

b) Saddle settings.

c) Reductions.

d) Speed and reduction interaction.

The other parameters show an effect from the mean response plots but the analysis of variance gives them a low level of confidence.

Variance (S/N):-

The mean response results plots are shown in Figure 24.

Significant parameters in order of significance are:

1) Tensions.

2) Work roll profile.

3) First intermediated roll position.

4) Reductions.

All of the other parameters show an effect on the mean response plots, but confidence in them is low.

7.5.2 Combining the Results - Analyzing the Best Parameter Settings.

By inspection of the results, assessments can be make as to what actions will reduce specific shape defects, also the process variability can be reduced. The parameter settings to achieve these aims are shown in Table 10.

To achieve overall improvements to strip shape those settings which reduce all of the shape defects should be adhered to. There are no parameter settings which fulfil this, so, a compromise must always be reached. Table 10 shows the parameter settings which are best for this task. The reasons for the choices are based on consideration of the parameters A-I as follows.

Parameter "A", work roll configuration (two flat or two cambered rolls, Table 8):-

From the reliable measure of "full centre" strip shape defect (Figure 21), level 3 is the best setting, ie: that giving the lowest mean response value.
The "average" strip shape results (Figure 22) also show that the best shape occurs when this parameter is set at level 3.

The "loose edge" strip shape results (Figure 23) show that level 3 gives the worst shape. However, the effect of this parameter on loose edge is low. That is, there is not much loose edge shape difference caused by this parameter.

The variance (S/N) results (Figure 24) show that this parameter significantly affects the consistency of strip shape. Level 3 setting gives the most consistent, that is robust, process.
Since the process variability is reduced, full centre and average strip shape is significantly improved, and loose edge is only affected slightly for the worst, setting level 3 is that chosen.

Parameter "B", first intermediate roll position:-

This parameter has the largest affect on strip shape out of all those tested.
From the measure of "full centre" strip shape (Figure 21) levels 3 and 4 are those producing the best shape.

Inspection of the "average" strip shape results (Figure 22) , setting level 2 gives the best strip shape. that is, rolling with a slight full centre until the last pass will encourage good strip shape.

The inconsistent measure of "loose edge" (Figure 23), shows that this defect can be reduced by aiming for levels 1 or 2 until the last pass of a rolling sequence. These parameter levels give either loose edges or full centre shapes.

Strip shape variability (Figure 24) is shown to be reduced by setting level 2. this is aiming for good strip shape on each pass of a rolling sequence.

There are two options from the results, a) aiming for a slight "full centre" (level 3 & 4) until the last pass will help to reduce full centre strip shape. There is a disadvantage in that the process variability will be increased, b) aiming for good strip shape throughout the rolling sequence (level 2) will give a good intermediate shape, and reduce the process variation. The best setting is level 2. The recommendation is to err on the side of rolling full centre (levels 3 & 4) rather than the loose edge (level 1).

Parameter "C", saddle settings:-

From the "full centre" strip shape mean response plots (Figure 21), setting level 3 is best. This setting gives a higher edge and less centre load. The next best setting is level 1 which gives an even mill loading pattern.

There is little effect on the "average" shape (Figure 22) after altering the saddle settings.

The loose edge measure of strip shape (Figure 23) shows that level 2 is preferred. The loading pattern which causes the lowest value of loose edge also causes the highest value of full centre strip shape defect.

There are two options of settings which will reduce the strip shape variability (Figure 24). Setting levels 2 and 4 which are either tapered or higher centre mill load pattern.

The choice of which saddle configuration to use is difficult. Setting the saddles to reduce full centre will increase loose edge. Reducing the process variance will increase the full centre defect.

Parameter "D", first intermediate roll taper geometry:-

This parameter has little effect on the full centre strip shape defect (Figure 21) setting level 1 or 2 can be used.

The average shape mean response plots (Figure 22) show that there is little effect on strip shape by use of the different profiled rolls used.

Loose edge strip shape defect (Figure 23) can be reduced by use of single tapered first intermediate rolls, that is level setting 1. This finding confirms experience in that level setting 1 has a steeper rolling angle. This would encourage less loose edge.

From the variance plots (Figure 24) there is little effect seen. There is a slight slope on the plot to show that setting level 1 is preferred.

Between these roll profiles tested setting level 1 is preferred. This is not to reason that different profiled rolls will prove worse in the future. The profiles used may not be the best to try. One reason why the level 1 rolls are better in these trials, is that the mill operators are used to them.

Parameter "E", Rolling speed:-

Speed setting level 2 (Figure 21) reduces full centre strip shape. Experience confirms this result in that increased speed, improves lubrication, reduces load and changes the rolls expansion, so producing full centre strip shape. (see section 4.5) [10].

From the average strip shape mean response plots (Figure 22) a slight improvement is seen at setting level 2.
Loose edge strip shape defect is reduced by rolling with setting level 1 (Figure 21), that is, higher speeds. This is opposite to the effect causing full centre.

The largest effect that rolling speed is seen to have is on the variance, (Figure 24). Variance is reduced when rolling with lower speeds, that is, setting level 2. The process is more stable at lower speeds.

Between the speed range tested there is not much affect on strip shape. That which is known already has been confirmed, faster rolling produces more centre fullness. The key to deciding which setting level to use is the process variance. The process is more robust if setting level 2, slower speeds, are used. The affect of this is probably more dominant on the last pass of a rolling sequence. Reducing the rolling speed on later passes will aid in producing better strip shape.

Parameter "F", reductions:-

Full centre strip shape defect is reduced by using setting level 1 for reductions. Level 1 means higher rolling loads due to less rolling passes in a sequence. The mill rolls bend to a greater extent and loose edges rather than full centre is formed.

From the mean response plots showing average strip shape (Figure 22), no effect is seen. The reductions have no effect on the average strip shape within the range tested.

Reductions have an opposite effect on loose edge to full centre. The mean response plots (Figure 23) show that level 2 is preferred for reducing loose edge. More passes mean less rolling load, more full centre.
The effects of reductions on strip variability (Figure 24) is seen to be negligible. The mean response plot does not change much.

Since it is not possible to predict what the last pass strip shape is going to be before rolling, the number of passes to give the best chance of rolling flat strip is indeterminable. Reductions do affect strip shape but their affect on shape can be overruled by other shape affecting parameters. The number of reductions to give are governed by mill load, power, lubrication, material properties, surface finish quality and rollers experience. Light last passes give better chance of producing good strip shape.

Parameter "G", Rolling mill operators:-

From the mean response plots (Figures 21 & 22) it is seen that one mill operator rolls slightly full centre and the other with slight loose edges. Differences between the levels are small.

Roller at level 2 produces slightly better average strip shape with less variance (Figures 23 & 24).

Parameter "H", tensions:-

Tensions at setting level 1 increase full centre strip shape, (Figure 21). Tensions at level 1 are high, this means that rolling loads are reduced. With lower rolling loads there is a tendency, due to roll bending characteristics, to roll full strip shape.

From the average shape mean response plots (Figure 22) tensions at setting level 1 improve strip shape.

Loose edge strip shape defects are reduced by tensions at level 1 (Figure 23). High tensions improve strip shape.
Strip shape variance is reduced dramatically when rolling with tensions at level 1. That is high tensions, (Figure 24).

Rolling should be carried out at the higher tension settings. Both average strip shape and variance are improved.

There is a compromise of tension settings between the shape defects caused of loose edge and full centre.

The faults caused by tension can be masked by other rolling parameters.

Parameter "I", speed and reduction interaction:-

From the plot showing the full centre mean response to this interaction (Figure 21), there is a negative interaction with no better or worse situations found. There will always be a compromise between speed and reduction for the best shape. Reduced rolling speed (level 1) and a reduced number of passes in a sequence (level 1) will reduce full centre shape.

The average strip shape mean response plots (Figure 22), show negligible effect.

From the plot showing the loose edge mean response to this interaction (Figure 23) the response is opposite to that for full centre. Increases rolling speed (level 2) and a larger number of passes in the rolling sequence (level 2) will reduce loose edge shape.

The variance plots, (Figure 24) show no real response. The speed and reduction interaction has no measurable effect an strip shape variation.

The measure of interaction gives no clear guide as to the preferred parameter settings.

The individual parameter responses give clearer indications to the settings which should be used.

8.0 WORK ROLL STRAIN.

8.1 INTRODUCTION.

The majority of work on strip shape assumes that shape is caused by a mismatch between the roll gap and strip profile [58]. This means that the strip is reduced by different percentages at different places across its width.

Experimental work has shown that the rolling parameters which effect the roll gap profile, have the greatest affect on strip shape. To improve strip shape it is necessary to control the roll gap profile.

Before modifications to roll geometries can take place, which will enable roll gap profile control, it is necessary to understand the behaviour of the roll gap.

A study has been made of the manner in which the mill work rolls bend. this will increase understanding of the roll gap behaviour. Two methods of studying the work roll bending behaviour have been considered:

a) Mathematical study.

b) An empirical method of roll strain analysis.

After studying modelling, and assessing the models used at present, this methods of gaining understanding was neglected. The reasons are:

a) Sendzimir cluster mill models in existence are not considered to be of sufficient accuracy. The models are mainly used to speed up shape control systems and not to ultimately describe shape and machine mathematically.

b) The effort required to model a mill of such complexity would prove inappropriate in terms of time.

The empirical method of finding the strains experienced by a work roll was chosen. the reasons are:

a) Real data which were quantifiable were to be gained.

b) The time scale involved was much shorter than modelling.

c) The necessary skills were at hand to complete the task.

8.2 EXPERIMENTAL TECHNIQUE.

To show the bending behaviour of a loaded work roll, the strains along the roll length are measured. Resistance strain gauges attached , at regular intervals to the roll surface, measured the strains. The change in resistance of the gauges due to their extension or compression are measured, from which the strains can be calculated.

An electronic data logger (E.D.L.), Figure 25, was used to gather all of the strain data. This allowed all of the strain results to be sampled at one particular instant, so ensuring consistent loading conditions. The time taken to gather data is very fast so enabling the evaluation of a lot of mill situations, without losing much production time. All of the gauges were zeroed prior to loading. The accuracy of the E.D.L. was checked against manual bridge balancing units. Here, each gauge was zeroed by manual adjustment of a variable resistor. Both measuring techniques showed similar results. This meant that the E.D.L. could be used with confidence.

Three strain measuring work rolls were manufactured as described below:

a) Ten rosette gauges were placed at equidistant intervals along the roll length (Figure 26a) to take the strain readings the roll was placed in the mill with the gauges at right angles to the roll bite.

b) Ten rosette gauges were attached at equidistant intervals along each side of a work roll (Figure 26b). That is the gauges were placed at 180° to each other. To take the strain readings the roll was placed in the mill with the gauges at right angles to the roll bite. This roll could measure the strains on the left and right of the roll simultaneously.

c) Ten linear gauges were placed in slots ground in the roll (Figure 26c). The gauges were placed at equidistant intervals along the length of the roll. The gauges were aligned longitudinally along the roll. This roll enabled the gauges to be positioned in the roll bite. The vertical bending behaviour was investigated with this roll.

Initial results from using roll 1 showed that there may be some degree of horizontal bending taking place (Figure 27a,c). To confirm this the second roll (b) was manufactured. All of the subsequent measurements were taken using rolls b and c.

8.3 MILL PARAMETER EFFECTS INVESTIGATED.

A large, but not exhaustive, set of strain tests were carried out. The tests represent all of the rolling parameters which can be varied with the mill not rolling (static).

The parameters investigated are as follows:

a) First intermediate roll position.

b) First intermediate roll profile.

c) load.

d) Strip or no-strip.

e) Work roll profile.

f) Saddle settings.

g) Castor differences. (Asymmetric support of the work roll).

There were three types of result collected:

a) Horizontal gauge results:

These were from gauges mounted on the surface of roll number 2. These gauges measure the roll elongation, bending, and longitudinal profile changes.

b) Vertical gauge results:

These were from gauges mounted on the surface of roll number 2. The gauges measure the roll squashing, circumferential profile change and compression.

c) The undercut roll gauge results:

These gauges are from the gauges positioned in slots ground in number 3 roll. The gauges measure roll elongation, vertical bending, and slot edge effects.

The testing procedure was:-

Place the roll in the mill in the correct orientation.

Initialize all the gauges (zero).

Set the statically adjustable rolling parameters.

Load the roll.

Take the readings.

This process was repeated for different measuring rolls, and different parameter settings.

8.4 RESULTS.

The strain results obtained were recorded on computer disc. There are too many strain results for their detailed presentation, however, relevant comparisons have been made and are presented.

The results are presented graphically with strain v the position of the gauge on the roll. Number 1 gauge is that at the front of the mill. The strain plots do not directly show the shape of the roll under load. They show the strains that the roll is experiencing. Basically the gauges show the increase of decrease in length of the particular portion of the roll being measured.

8.4.1 Typical Strain Results Plots. (Figures 27-34)

Typical plots of the horizontal gauge results consistently show two peak values of strain. One strain peak is larger than the other. These peak values occur under all parameter conditions. The peaks occur at the position where the parallel section of the first intermediate (shape control) roll changes to a taper. That is, at the transition between the flat and taper section of the first intermediate rolls. The largest peak occurs at one side of the roll at the front of the mill, then changes to the opposite side at the rear of the mill. The minor strain peak is often so small that it is not easily detectable. When the results from both sides of the roll are plotted on the same axis, they are seen to cross over. Between the top and bottom positions of the measuring roll in the mill there is a reversal of strain results. The major strain peak occurs at opposite sides of the roll.

Typical vertical gauge result plots are inverted horizontal plots. The values of strains recorded are less, that is, approximately one third of the value of the horizontal plots. Mostly, the strains recorded are negative or compressive. However, at the end of the rolls there is a tendency for tensile strains to be seen. There are two strain peaks shown on the plots. One peak is of greater value. On one side of the roll the major peak is recorded at the front of the mill and vice-versa. When plotting the strain results from both sides of the roll on the same axis the plots cross over. When comparing the top and bottom results, that is, with the measuring roll in the top half or bottom half of the mill cluster, the results reverse. The major peak changes from one side of the roll to the other.

Nearly all of the results taken when using the undercut measuring roll, show typically shaped plots. A large peak of strains is seen which occurs at the place where the taper transition of the first intermediate roll is in direct contact with the gauged work roll. The peak is severe and rapidly reduces to a level strain condition. There is a small strain peak recorded at the position where the measuring work roll is opposite the roll in contact with the first intermediate roll taper transition. Beyond the taper transition point, on both sides of the mill the strains reduce dramatically.

8.4.2 Individual Effects of Mill Parameters.

a) First intermediate roll position, Figure 27a-c:

From the horizontal and vertical strain gauge results, no pattern is shown which can be related to first intermediate roll position.

The undercut roll gauge results show that alterations in the first intermediate roll position dramatically affect the magnitude of the peak strain. This difference is larger than any other parameter effect under investigation. The strain peak gets wider at its base and the maximum magnitude of strains change with altering first intermediate roll positions. As the point of taper transition is moved towards the centre of the mill then the magnitude and width of the strain peak increases.

b) First intermediate roll profile, Figure 28a-c:

The different profiles under investigation were the standard single taper and a triple tapered roll. Details of the profiles are shown in Figure 28a.
No strain pattern seen can be related to the different roll profiles for both the horizontal and vertical gauge plots. There is a hint from the horizontal gauge plots that the strain peak is less pronounced but broader in effect with the triple taper. There is also a hint from the vertical results that the plots between the right and left of the mill cross over in a more severe manner.

From the undercut roll gauge results it is seen that, when using the modified triple tapered first intermediate rolls, the stain peak is less severe. The strain peak is also seen to affect less of the strip width, that is, it is narrower.

c) Loading differences, Figure 29a-c:

From the horizontal gauge plots it is shown that with increasing load there is an increase in the values of measured strains.

The plots between the right and left of the mill cross in a more severe manner with increasing loads.

The vertical gauge plots confirm the trends of the horizontal gauge plots. With increasing loads there is an increase in compressive strain values.
The undercut roll gauge plots reveal that, for increasing loads, there is a steady increase in strains. Peak strain values increase for each increase in load. The width of the strain peak does not alter with load differences.

d) Strip in or out of the roll bite, Figure 30a-d:

The horizontal gauge results show that the strain peaks are different with strip in or out of the roll bite. With strip in the peaks are more pronounced especially at the end of the roll which is not in direct contact with the taper transition of the first intermediate roll. The nature of the peak is not independent but it relates to first intermediate roll profile position, load etc.

Examination of the vertical gauge results shows, with strip in, a higher and altered positioned strain peak. The decrease in strains at the edges of the plots is more severe with strip in.

From the undercut roll strain plots the major difference between strip in or out of the roll bite is that the edge strains reduce in a different manner. With strip in the strains reduce more severely.

e) Work roll profile, Figure 31a-d:

Due to the measuring rolls being parallel ground the effects of work roll profile are limited to one roll being ground with a camber. The only results available at present to show the effects of work roll profile were taken with strip in the mill. With this situation there is a slight masking of the measurable effects of work roll profile on strains.
The horizontal and vertical gauge results show little measurable effects of different roll profiles. There is a trend showing that with flat rolls, there are higher peak compressive strains than with cambered.

From the undercut roll strain results there is no measurable difference on strains due to work roll profile. With the mill set-up used the measuring technique is not sensitive enough to measure the effects of one cambered roll on vertical work roll bending.

f) Saddle settings, Figure 32a-c:

There are no clear effects on the recorded strains of the horizontal, vertical and undercut roll gauge results, due to saddle adjustments (mill loading pattern).

g) Castor differences, Figure 33a-d:

Only horizontal and vertical strain plots are available to show the effects of castor differences on roll bending. There are no clear effects on the recorded strains due to castor differences (work roll support symmetry).

h) Flat ground tapers, Figure 34a-c:

Tests were carried out with a level mill set up, that is, with all of the mill rolls ground flat to help in the analysis of parameter results. A set of control results was gained.

The horizontal gauge plots show a level trace. The left and right of the roll strain plots cross over a number of times at the mill centre. At the ends of the mill there is a slight separation of the plots. This separation is in opposite directions for each side of the mill. The strains on the right of the roll are higher at one side of the mill and vice-versa.

The vertical gauge results show consistent values of compressive strain across the mill. At the mill edges there are slight decreases in compressive strains recorded. There is a separation of the plots seen at the ends of the mill. This confirms the horizontal gauge results.

From the undercut roll strain plots there is a consistent level of strains across the mill. There is only a slight decrease in strains recorded at the mill centre.

8.5 INTERPRETATION OF THE RESULTS.

There are a number of different factors which can effect the way in which the roll surface elongates, or compresses. To analyze the results there needs to be some estimation of the effects of each of these factors. These strain effecting factors are as follows:

a) Roll extension.

b) Roll profile change.

c) Ground slot profile results.

d) Roll bending.

a) Roll extension.

The extreme loads applied and low level of metal to metal co-efficient of friction may mean that the roll elongates. This elongation would be measured as strain on both the horizontal gauges and the undercut roll gauges.

The plots showing the horizontal gauge results for different loads (Figure 29) show that the effects of roll extension are small. The individual plots are not displaced from each other and only the peak strain values are affected. If the extension effects were large then the plots should be displaced from each other by amounts relating to the applied load.

b) Roll profile change.

A loaded work roll will change its profile along its length, and through its cross section. The manner with which the profile changes is related to the roll material properties, profile, the load applied, and the manner of support. Estimates of the profile change are shown in Figure 35.

Any differential loading of a work roll along its length will cause a longitudinal profile change. This variation in profile will affect the roll surface geometry and hence the strains recorded.

Alterations in roll profile would be expected at points of loading alterations. There is no means of isolating these effects from roll bending.

There are two areas to consider with cross sectional roll profile changes. These are, the strains caused by the changing roll radius, and those caused by direct compression. If a cuboid block was loaded, then from Poissons ratio effects, the strains in the direction of load should be three times that in the plane at right angles to the load. Measurements of horizontal and vertical gauge strains show the stress in the direction of load to be one third those in the plane at right angles to the load. One explanation for this is that a high degree of geometry change and compression occur at the same time, hence corrupting the results.

c) Slot edge effects.

Since the gauges on the undercut roll are sunk into recesses, and the load is applied around these, then the behaviour of the slots affect the strains experienced.

Whilst loading the undercut roll through a level mill set up, that is with all rolls ground parallel, a static strain level of $210\mu E$ is seen (Figure 34c). When loading the horizontal gauged roll in the same manner a strain value of $75\mu E$ is seen. If elongation alone was being measured then these results would be similar. The slots must have an effect on the strains measured. These effects are shown to be consistent, and so can be taken into account when analyzing the results.

d) Roll Bending.

This can be broken down into two areas:

i) Horizontal roll bending.

ii) Vertical roll bending.

i) Horizontal roll bending.

Typical plots show that between the right and left of the work roll opposing strain patterns, or separated plots, occur. The plots cross over at the mill centre. This type of plot is indicative of bending. The position of the gauges means that horizontal bending and not vertical is recorded. It has been shown that the strains are recording either roll profile changes, or roll bending or a combination of these.

The arguments in favour of roll bending occurring are:

- The consistent strain pattern for different loading conditions.
- The difference in strains between the right and left of the mill.
- The crossing over of the strain plots from the front to the back of the mill.
- The parallel plots recorded when loading the roll through the flat ground roll cluster.

ii) Vertical roll bending.

The roll bending strains measured by the undercut roll show the vertical bending of a work roll. The high strains measured next to the taper transition of the first intermediate roll show that bending is occurring.

The strains measured are large compared to the roll extension and slot edge effects (Figure 34c).

Strains are highest at the point of contact with the first intermediate roll taper transition. The taper transition is at the front of the mill with the roll in the top half and vice-versa. This lack of symmetry is shown by the strain plots. There is asymmetry between the top and bottom and between the left and right of the mill.

Loaded mills experience flexing, this flexing is translated into work roll bending. Using the undercut roll this flexing can be found. From the results taken with a parallel ground roll mill set up (Figure 34c) a slight curving of the plots is revealed, this indicates the amount of mill flexing. The strains recorded are lower at the centre than the sides of the mill. There is evidence that there is slightly higher mill load at the back (drive) side of the mill.

Comparing the plots of the flat ground roll mill set up (Figure 34c) and typical results of undercut roll strains there is a levelling out of the plots at the centre of the mill which coincides.

8.6 ANALYSIS BY PARAMETER AND SHAPE.

a) First intermediate roll position.

When comparing all of the plots it is clear that the first intermediate roll position dominates all the other parameters in its effect on roll strains.

By modelling the roll as a beam, making certain assumptions for boundary conditions and loading, the dominating effect of taper length can be seen, Appendix 2.

"Over rolled centre" or "full strip shape" occurs when the first intermediate rolls are moved towards the mill centre. The increase in magnitude and broadening of the strain peaks shows why this would occur. The work roll bends so that it effects the strip centre in a broad sense. "Loose edge shape" occurs when the strain peak is low and towards the strip edge. Quarter buckle occurs when a high and narrow strain peak affects one section of the strip.

b) Different first intermediate roll profiles.

Within the range of roll profiles tested there is little effect caused by this parameter on strip shape. There are more dominant shape affecting parameters. The horizontal bending results indicate a more pronounced horizontal roll bending with the modified tapers. The undercut roll results indicate that the strain peak occurs towards the strip edges with the modified roll. This would encourage loose edge strip shape.

c) Loading differences.

There is a steady increase in strains with increasing applied loads. The strain peaks broaden slightly. The vertical bending of a work roll affects the same amount of strip width for different loads. The severity of roll bending increases but is localised. From this we can see that quarter buckle shape defect, caused by localised overrolling, will be more likely to occur with high rolling loads. High rolling loads tend to move the strain peaks towards the mill edges, so encouraging loose edge strip shape.

Higher rolling loads made the roll strains more sensitive to other parameters. Therefore, less control over shape can be exercised at higher rolling loads.

d) Strip in or out.

When comparing the 5" (127mm) or 7" (178mm) length of taper, first intermediate roll strain results, with strip in or out, it can be seen that the strain peaks are different. This would indicate that for different material geometries the first intermediate roll profiles should be different.

The sudden drop off in strains shown on the plots with strip in is due to the work roll being free at the strip edge. The overhang of the work roll, that is not in contact with the strip, causes compressive strains to be recorded.

e) Work roll profile.

The results show that work roll profile has little effect on roll strain patterns. Experience and past work has shown that work roll profiles measurably affect strip shape. Work roll profiles effectively modify the first intermediate roll profile and help to make the roll bite more symmetrical.

f) Saddle adjustments.

Strain patterns showing the effect of saddle adjustments reveal no clear trends. Previous work has shown that throughout a rolling sequence saddle adjustments have some measurable effect on strip shape. Large saddle alterations shown no strain pattern change.

g) Castors.

No measurable effect on work roll strain is seen by altering the castors. Rolling trials have shown that there may be some effect on strip shape caused by off-setting the castors. The effect is small and difficult to confirm.

h) Flat tapers.

The lack of strain peaks on any of the results using flat ground tapers, proves that the strain peaks are related to the first intermediate roll position. The horizontal strains show that, to a small extent, the work roll is elongating whilst under load. The undercut roll results show that the slot edge effects are more dominant than the roll extension. The slot edge effects are consistent so the amount of roll bending can be found, as can the mill flexing characteristics. There is a slight amount of mill flexing at high loads.
That the mill is internally aligned correctly is shown by the consistent value of horizontal and vertical gauge results. Any variation across the mill would show that the work rolls are crossing. Localised increases in pressure may force the rolls sideways. This is the case when there is a tapered profile ground on the first intermediate rolls.

9.0 INVESTIGATION INTO THE EFFECTS OF FIRST INTERMEDIATE ROLL POSITION AND LOAD ON WORK ROLL BENDING.

9.1 INTRODUCTION AND EXPERIMENTAL PROCEDURE.

Since the position of the first intermediate rolls and load dominates strip shape it is necessary to gain a more clear understanding of their effects.

The specific objectives of this work are as follows:

- To examine the effects of the first intermediate roll position on work roll bending, with strip in the mill.
- To predict the best first intermediate roll position which will give good strip shape.
- To relate work roll bending to strip shape.
- To gain ideas for improved roll profiles.

Work roll strain measurement as described in section 8 was used for this work.

Two methods of strain measurement were used. That of measuring the vertical bending and that of measuring the horizontal bending, of a work roll. For all of the tests strip of dimensions 12" (305mm) wide by 0.01" (0.25mm) thick was held centrally in the mill. After positioning the work rolls, first intermediate rolls, and strip in the mill, a pre-set load was applied. The strains experienced by the roll were measured by an electronic data logger (E.D.L.). A cycle of removing the load, resetting the rolling parameters, and the recording the strains was carried out. This procedure was repeated for seven different first intermediate roll positions and two different loads.

9.2 RESULTS.

There are three sets of results to be analyzed, these are:

a) The vertical bending strains measured with a 50 ton mill load (Figure 36).

b) The vertical bending strains measured with a 100 ton mill load (Figure 37).

c) The horizontal bending strains measured with a 100 ton mill load (Figure 38).

a) Vertical roll bending strains (50 ton load) (Figure 36).

Altering the position of the first intermediate rolls made no difference to the shape characteristic of the strain plots. Whilst the shape characteristic did not change, the magnitude of the strains measured altered significantly. As the first intermediate roll taper transition point is moved towards the centre of the mill (less flat), the, the maximum strain values increase. A pronounced strain peak is seen where the taper transition of the first intermediate roll directly impinges on the work roll. The strains generally reduce from the strain peak, to a region around the opposing first intermediate roll taper transition. This reduction in strains is always in the form of a curve. After the opposing first intermediate roll taper transition, the strains steeply reduce. After the strip edge the strains go compressive. Between gauge positions 3 and 4 the slope of the traces go from positive to negative. This is with different first intermediate roll positions.

b) Vertical roll bending strains (100 ton load) (Figure 37).

General observations about the roll bending strain plots with 50 ton load are the same as for the 100 ton load.

The only difference being the magnitude of the strains recorded. There can be up to 200μE difference between the 50-100 ton load plots.

c) Horizontal roll bending stains (100 ton load) (Figure 38).

Two strain peaks occur near to the first intermediate roll taper transition positions. The peaks nearest to the rear (drive) side of the mill are greatest. The plots showing the left and right strains of the mill roll, for the same mill set up, cross over.

9.3 ANALYSIS.

Results in section 9.2 have shown that first intermediate roll positional changes and rolling load have large effects on the magnitude of work roll strains. From this it can be concluded that these parameters have significant effects on strip shape. The relative effects of load and first intermediate roll position are shown. From this a guide can be gained as to the amount of first intermediate roll movement necessary to compensate for load variations. These variations are caused by speed/ lubrication/ thermal effects [8,10].

An indication that the first intermediate roll position that will give best strip shape can be predicted is given from gauge positions 3 and 4 on the plots (Figures 37 & 38). Between these two gauge positions the slopes of the individual traces go from negative to positive dependant on the first intermediate roll position. The slope nearest to the horizontal, which is in practice near to typical rolling position, may indicate the preferred roll position.

Measurement of strip shape carried out indicated that there is no rolling situation where perfectly flat strip is obtainable. This work is confirmed by a mill model forwarded by T Matsuda [32]. Typical strip shape defects can be limited to the estimated bending of a work roll shown by the strain results. A sequence of shape defects with their respective roll gap profiles caused by roll bending is shown in Figure 39. There is no position of "neutral", that is perfect strip shape.

10.0 INDIVIDUAL TESTS ON THE EFFECTS OF ROLLING PARAMETERS ON STRIP SHAPE.

10.1 INTRODUCTION.

During the course of the project on strip shape it has been necessary to individually test various rolling parameters. The reasons for these tests are:

- To help in formulating the parameters to test and settings in more advance work.
- For confirmatory reasons. That is, to check whether the parameters have any real effect or what magnitude of effect do they have? etc.
- To carry out detailed work on significant shape effecting rolling parameters.

The results from the trials were limited in that only the isolated effect of each parameter is shown. Many of the rolling parameters affect each other with regards to producing strip shape.

Taking into account these limitations, useful inferences can still be drawn from the work. Initially a set of typical strip shape measurements were taken so that comparisons could be made with subsequent work.

This work observes "trends" in shape differences, this is because of the complexity of the rolling process and the interacting nature of rolling parameters in their effects on shape.

The individual parameters tested are:

a) First intermediate roll profile.

b) Work roll profile.

c) Saddle adjustments.

d) Offset castors.

e) Speed

f) Tensions

10.2 METHODS OF INVESTIGATION.

There have been various methods used to assess the different effects of rolling parameters on strip shape. The major ones are:-

- Keep a record over a period of time of the general strip shape differences caused by that particular parameter. The trends of shape can be seen if enough samples are taken.
- Take one coil and carry out a series of tests on it. This ensures that, as far as possible, all things except the altered parameter are held constant.
- Take one coil and split it so that the rolling of two similar coils takes place. Everything is held as near constant as possible for the two coils except for the parameter setting under test.

10.3 RESULTS.

10.3.1 First Intermediate Roll Profile.

The work on "first intermediate roll profile effects on strip shape" is a major and continuing area of work. There is no doubt that the position of the first intermediate rolls affects strip shape more than any other rolling parameter. To exert more control over strip shape it is necessary to find out if the effects of the first intermediate rolls can be altered. The primary method of changing the rolling characteristics of the rolls is by changing their ground roll profile.

Tests have been carried out using a variety of roll profiles, the details of which are shown in Figure 41.

For identification purposes the rolls are named as follows:

- a) Ordinary profile
- b) Double taper
- c) Triple taper with back taper
- d) Triple taper with back taper
- e_1) Blended taper
- e_2) Blended taper with back taper
- f) Complex profiles

Initial observations showed that a large number of strip shape samples had quarter buckle and loose edge. Typical strip shape was that of quarter buckle on one side and loose edge on the other side of the strip. Tests also proved that the first intermediate rolls are the dominant strip shape affecting rolling parameters. From this it was decided that work on improving strip shape by modifying the first intermediate roll profiles was necessary.

Previous work, section 2, has shown that modifying the roll profile so that the transition between the parallel and tapered section of the roll is less severe, may reduce quarter buckle.

The first investigation step was to produce rolls having a double taper, Figure 41b. After encouraging results from this a triple taper transition was tested, Figure 41c.

Further work on the behaviour of a work roll under load, section 2, indicated that a more symmetrical mill load may help to improve strip shape. From this a back taper was placed on the rolls, Figure 41d.

As soon as a manufacturer with the ability to grind curved transitions on a roll was found, these were ordered and tested, Figure 41e.

a) Ordinary Taper Strip Shape, Figure 42a-b:

The results shown in Figure 42 are of typical strip shape. Strip shapes shown in Figure 42a are from using 178mm (length of taper) tapered first intermediate rolls (for rolling narrow strip). Strip shape results using 127mm tapered first intermediate rolls (for rolling wide strip) are shown in Figure 42b. There are a large range of strip shapes that can be produced. A loose edge sample, Figure 42b, has a high value of shape at the edges, and a quarter buckle with loose edge sample. Strip shape samples with differing amounts of quarter buckle and loose edge are seen in Figure 42b.

Although a full range of strip shape can be produced by the rolling mills, that is, loose edge, quarter buckle, full centre, herringbone etc., combinations of these are most likely to occur. From a large number of rolling trials undertaken, the predominant shape produced was found to be a quarter buckle with one loose edge. The magnitude of the shape defects varied considerably. Comparisons can be made between altered parameters and typical strip shape, but because of the large difference in typical shape measured, the results are only to be used as a guide. No firm conclusions can be drawn from comparisons against typical shape.

b) Double Taper Strip Shape, Figure 43a-c:

The results shown are of the shape produced by using double taper and ordinary first intermediate rolls. Strip shape samples are taken form the centre of coils so that they are from steady state rolling conditions. Shape samples using double tapered rolls are shown against shape samples from the same coil using ordinary tapered rolls. This ensured that, as far as possible, everything except the first intermediate profile was constant. Results from using 178mm first intermediate rolls are shown in Figure 43a and b. Results from using 127mm first intermediate roll are shown in Figure 43c.

Figure 43a indicates that by using the double tapered first intermediate rolls, a general improvement to strip shape is made. This result is consistent over the four trials carried out. Two of the coils show good shape produced by rolling with double tapered first intermediate rolls. Two of the coils show poor shape produced by rolling with ordinary tapered first intermediate rolls.

Figure 43b shows similar strip shape samples. Using the double ground tapers a loose edge has been produced at one side of the strip. This shows a tendency for double tapers to produce more "loose edge" and less "full centre/quarter buckle" strip shape.

Figure 43c. From the result showing the shape effects on wider strip, that is using the 127mm tapers, there are no clear strip shape effects. There seems to be a slight reduction in the amount of quarter buckle produced when using the double tapered first intermediate rolls.

c and d) Triple Taper Strip Shape, Figure 44a-d.

Strip shape produced by rolling using 178mm triple and back taper profiled first intermediate rolls is shown in Figure 44a and b. Shown in Figure 44c and d is strip shape produced by rolling with 127mm triple tapered first intermediate rolls. All of the graphs show a shape history, that is samples of start, middle and end, or start and end of a coil. The history shows the way in which the shape changes throughout rolling. There are no results showing direct comparisons using the same coil for ordinary and triple first intermediate rolls. This is due to the lack of suitable material being processed. The shape plots shown allow general comparisons to typical shape to be made.

Figure 44a. A typical "quarter buckle" and "loose edge" shape is shown.
The middle strip shape sample is the best. This sample is representative of the majority of the coil. The start sample has a large "loose edge". The end sample exhibits more "quarter buckle".

Generally, a fairly good strip shape has been produced. Most of the coil is below 20 I-units, this is good for rolled shape.

Figure 44b. A slight "quarter buckle" strip shape has been produced through most of the coil. The middle sample shows excellent shape and is below 10 I-units. This value corresponds to stretch-levelled material. The start shape shows "loose edge" and the end shape shows a higher degree of "quarter buckle".

Figure 44c. A significant "quarter buckle" to "full centre" is the dominant shape produced throughout this coil. The start shape is good and the shape gets progressively worse (more full) as rolling proceeds. The shape is of a typical to high value for as rolled products.

Figure 44d. A fair strip shape sample is seen here. The start shape is typically "loose edge". The end shape shows less "loose edge". Assuming that the middle sample, that is for the majority of the coil, is somewhere between the two then good strip shape of below 10 I-units has been produced. This test was carried out on a softer material than the other trials, so does not show a fair comparison. It shows that on a soft material good shape can be produced.

e) Curved Intermediate Roll Strip Shape, Figure 45a-c:

Strip shape results using 178mm first intermediate rolls are shown in Figure 45a. Results for 127mm first intermediate rolls are shown in Figure 45b and c.

All of the results show comparisons, that is from trials carried out on the same coil with the only difference being the first intermediate roll profile.

Figure 45a. Indicating poor strip shape from both the ordinary and curved rolls. The shape is of severe "full centre" to "quarter buckle". Using the curved rolls a reduction is shape severity of about 20 I-units has been achieved.

Figure 45b. Both strip shape samples show a large "quarter buckle". The size of "quarter buckle" is typical of that normally produced. Using the curved intermediate rolls the severity of shape has been reduced by about 10 I-units. Although the severity has been reduced there are "quarter buckles" on each side of the shape sample using the curved intermediate rolls. There is "quarter buckle" only on one side of the strip using ordinary first intermediate rolls.

Figure 45c. This graph shows the start and middle samples of a coil rolled on curved and ordinary intermediate rolls. Both of the samples from the ordinary rolls show a severe "quarter buckle" at one side. Both of the samples from the curved rolls show good shape over the majority of the coil width, with a "loose edge" on one side. The majority of the coil shows better strip shape when using curved intermediate rolls.

f) Complex First Intermediate Roll Strip shape, Figure 46.

The results showing the shape produced when using complex rolls are only a one-off trial. There are no comparisons available. The shape produced can be related to typical values of shape.

The aim with these rolls was to reduce the sensitivity of the rolling process to alterations of roll position based on strain work in section 8 and experimental design work section 5. Because of this, mill operators comments have been taken into account.

The graph shows the start, middle and end shapes. The start sample shows good initial shape. There are slight "loose edges", one being more sever than the other. The middle sample shows a fair shape. There are no "loose edges" but there are symmetrical "quarter buckles" of up to 25 I-units. Typical rolled shape can be up to 50 I-units. The end sample shows a poor shape. One edge is very loose (long), and there is a large "quarter buckle". The majority of the coil shows fair shape.

The mill operator (who was not very experienced) could easily roll using these complex rolls. On making first intermediate roll lateral adjustments a large movement produced little difference to strip shape. This is not normal, usually small roll movements have a large affect on strip shape. The operator expressed surprise at this. A large movement of the rolls had relatively little effect on strip shape but a slight strip alignment change altered strip shape significantly.

10.3.2 Work Rolls.

Most of the trials involving testing the effects of different work roll profiles was covered in experimental design work, section 5. Work roll profiles significantly affect strip shape. Different profiles modify the behaviour of roll bending with respect to the first intermediate roll profile. Common use is made of slightly cambered rolls, usually on narrow widths of strip.

Some trials have been carried out using bored rolls. That is, work rolls with a hole through the centre. The reason for trying this was in an attempt to increase the tension feedback (attenuation) effect [40]. An effective increase in the rolls elasticity, by boring a hole in the centre, would allow more sensitivity to applied loads. There would also be an increase in the rolling load necessary for a given reduction. Using a finite element model different diameter holes were tested for safety, and increases in roll deformation. A hole diameter of 12.5mm was found to be appropriate.

Bored work roll strip shape trial, Figure 47a-b:

Two graphs are shown, one with narrow strip, 178mm first intermediate rolls. One with wide strip 127mm first intermediate rolls. Comparison tests are shown. The same coil is used for the trials, one test was run using solid rolls and the other using bores rolls.

For the wide strip (Figure 47a) both strip samples show "loose edge" but their overall shape is fair. The strip rolled on solid rolls shows less "loose edge" and better shape than that rolled using the bored rolls.

For the narrow strip (Figure 47b) there is a similar result. The solid rolls produce the better strip shape. The bored rolls produce more "loose edge". The shape plot is, however, slightly misleading. The shape at the edge is not "loose" but has been observed to be "full". This means that the roll is bending in a more sever manner over the first intermediate roll profile. The major difference between a bored and solid work roll is not the degree of flattening that occurs but the difference in roll bending.

10.3.3 Saddle Adjustments.

Loading across the mill can be altered by saddle adjustments. Bearings which transmit the load to the mill housing can be individually adjusted so changing the mill loading pattern. The effects of these adjustments were investigated in a variety of ways. Using experimental design techniques, the effects of this variable throughout a rolling sequence on relatively soft material (316 austenitic) has been investigated. The effects of saddle adjustments on short test runs and a complete rolling pass have also been investigated.

Saddle Adjustment Strip Shape Trials, Figure 48a-b:

Results from a trial involving altering the saddles for a complete pass of a rolling sequence on hard material (301 HT austenitic) is shown in Figure 48a. The same coil was used for both saddle configurations. The coil was split in half so that all things except the saddle settings were common. Two graphs are shown, one where alterations to the addles were made for a single rolling pass hence steady state rolling conditions were reached, the other over small test runs.

Figure 48a: Over a complete rolling pass both samples show similar shape. The shape produced is that of loose edges. Saddle differences show undetectable effect on strip shape.

Figure 58b: Over short test runs the shape plots reveal that saddle alterations do not seem to change the strip shape. All of the plots show typical shape of quarter buckle and loose edge. The rolling mill operators set-up shape dominates that which is produced.

10.3.4 Offset Castors.

Work showing that the behaviour of a roll under load, by measuring the strains experienced by it indicates that the work rolls bend horizontally. This horizontal bending is though to have links with quarter buckle and cross camber strip shape defects. In an attempt to reduce the horizontal bending of the work rolls, the mill casters have been off-set. The castors are the bearings through which rolling load is transmitted to the mill housing. The casters can be adjusted to allow for different roll diameters. The top and bottom sets of casters are linked mechanically, but between the right and left of the mill they are independent. Altering the castors off-sets the mill geometry and also allow, within limits, the work roll to be supported at different positions. Supporting the work roll at lower positions should reduce its horizontal bending.

Offset Castor Strip Shape Trial, Figure 49a-b:

There are two graphs shown, one is a comparison between offset and even castor settings. The other is a shape history showing the start and end of a coil when rolled with offset castors.

The first plot (Figure 49a) shows the comparison with the castors set "even", the strip shape is poor with two "loose edges". With the castors offset a typical strip shape is seen. The sample shows a slight "quarter buckle" and one "loose edge". If the offset castors restricted horizonal roll bending, as was hoped, then a reduction in "quarter buckle" should have been the outcome. The result seen is a reduction in "loose edge".

Figure 49b shows the change in shape through a coil with offset castors. The overall shapes of the start and end of the coil are good. A typical shape of "quarter buckle" at one side is seen. When comparing these shapes to typical plots of normal rolling, no conclusions as to any real effects can be drawn.

10.3.5 Speed.

It is known that rolling speed strongly affects strip shape, section 2.3.
The temperature of the mill changes so affecting thermal camber. Lubrication improves with increasing speed so affecting mill load. Strain rates change so the material rolled behaves differently.

Speed affects on Strip Shape Trial, Figure 50:

The results plotted are from single trials carried out on a single coil. Everything except the speed was constant. The results show a clear shape progression which is related to strip speed. At slow speed the strip shows "loose edge". Increase the speed and the amount of "loose edge" reduces and a "quarter buckle" with one "loose edge" has developed. Therefore, increasing speed increases "centre fullness/quarter buckle". The reduction in rolling load with increased thermal camber accounts for this change.

10.3.6 Tensions.

Tension applied to the strip reduces the rolling load, and affects the position of the neutral point in the roll gap.

Tension enables the necessary reductions, keeps the strip on line, and ensures satisfactory strip shape. Mill designers recommend tension up to one third of yield strength. To improve on strip shape higher tensions can be used.

Tension Trial Strip Shape, Figure 51a-b:

Both tension trials show comparisons done on a single coil. That is, that the only difference is the tensions used. The relative tension differences were the same throughout the complete rolling sequence.

From Figure 51a two samples having a severe "loose edge" are seen. The degree of loose edge is far less on the sample rolled using high tensions, and there is a wider section of good strip shape. Both the samples were taken from the middle of a coil so ensuring consistent steady state rolling conditions, these were representative of the majority of the coil.

Only the start and end samples of the coil under test were available for trials, shown in Figure 51b. The start of the coil using both high and normal tensions show "loose edge". the high tension sample has one "loose edge" whereas the normal tension sample has two "loose edges". Both end samples show good shape, with slight "quarter buckles" and "loose edges". There is slightly less "loose edge" on one side of the high tension sample. Increased tensions reduce the "loose edge" strip shape defect.

10.4 ANALYSIS.

10.4.1 Strip Shape Produced by First Intermediate Roll Profile Differences.

Ordinary Taper Strip Shape:

The predominant typical strip shape is that of "quarter buckle" on one side of the strip with a "loose edge" at the other. There is a large variety of different types and magnitudes of "typical shape" to compare improvements/alterations in the process.

Double Taper Strip Shape:

Improvements to strip shape are made when using these modified intermediate roll profiles. Although the improvements are slight, the trend is clear. "Quarter buckle" strip shape is reduced using these rolls but there is a slight increase in the tendency to produce "loose edge".

Triple Taper Strip Shape:

No direct comparison samples are available, but these profiled rolls produce a reasonable shape. Whether this shape is better than that which would be produced by using double tapered, or ordinary rolls, is not clear.

Curved Intermediate Roll Strip Shape:

These rolls produce an improvement over using ordinary rolls. The comparisons show that "full centre" and "quarter buckle" are reduced. No comparisons between these rolls and other roll profiles other than ordinary have been made. These rolls reduce "quarter buckle" and "full centre" by a significant amount.

10.4.2 Strip Shape Produced by Complex First Intermediate Roll Profile.

Although a single test cannot prove consistent improvements to strip shape, the results show that good shape can be produced by these modified rolls. "Quarter buckle" may be reduced by further blending modifications to the roll profiles. The operators observations prove that the process has become less sensitive to the roll position. Large intermediate roll movements with no strip shape change proves this. Mill bending must play a large part in producing strip shape, this is shown by large movements in taper position having little effect on shape, whereas a small strip line difference had a large effect. Further research with these rolls will give the capability of improving strip shape.

10.4.3 Strip Shape Produced by Bored Work Rolls.

By decreasing the second movement of area by the roll it was found that the roll bent more easily in the vertical plane. There was no improvement to strip shape from the enhanced tension attenuation. Roll bending affects strip shape more than tension attenuation.

10.4.4 Strip Shape Produced by Saddle Adjustments.

Altering the saddles for a single rolling pass on a hard material has little effect on strip shape. Altering the saddles over short test runs has no measurable effect on strip shape. For there to be any benefit to strip shape from altering the mill loading by saddle adjustments, the best configuration must be held throughout the rolling sequence.

10.4.5 Strip Shape Produced by Offset Castors.

No definite conclusions can be drawn as to the effect of offset castors on strip shape. There is some evidence hinting that offset castors can reduce "loose edge".

10.4.6 Strip Shape Produced by Speed.

Speed affects strip shape significantly, with increasing speed the amount of centre fullness increases and loosed edge decreases. Mill operators experience is the method used to estimate the start shape necessary. The reduction, material type, speed, tensions and load all need to be taken into account.

10.4.7 Strip Shape Produced by Tensions.

High tensions improve strip shape. The front tension mostly affects shape. The back tensions mainly reduce the "herringbone" and "loose edge" strip shape defects.

11.0 DISCUSSION.

Much of the published work on strip shape control has difficulty in finding enough supporting evidence. Some of the problems which have been found, are because there is a lack of real consistency between different coils of steel rolled. Coils which seem similar in all respects, when rolled in the same manner, will often show completely different shape. To undertake experimental work which encourages all of the strip shape affecting parameters, requires a large number of coils. These are not available in enough quantities of consistent quality and geometries to do the tests required. Much of the work is done on specific rolling mills which relate to that mill in detail.

Due to the low number of narrow mill strip manufacturers, and the nature of their business being relatively small there has not been large resources invested in research. Work published has shown in general the strip shape affecting parameters mostly from a mechanical bias. There is not much work relating metallurgical properties to shape. There has been a substantial amount of work in recent years on producing on-line shape measuring devices. Many producers using these devices have problems with them. There is in the authors opinion insufficient on-line and off-line evidence to prove that these devices work consistently.

This project took the form of more directly investigating the mechanical strip shape affecting parameters. This was because any improvements suggested by metallurgical findings would not be able to be implemented within the scope of this report and so produce real benefits to the industrial sponsor.

Another reason is that the expense involved in producing different materials for rolling is outside the scope of this research. Work had to be carried out without any form of on-line strip shape measurement. This is because there was no device available, and, as the project went on it became clear that the devices on the market had not shown great quantified improvements to strip shape. The shape measuring devices would prove more accurate on wide rather than narrow strip mills. On-line shapemeters are high cost instruments and it was shown that at present the parameters of adjusting saddles which they would control, in order to improve strip shape, would show little benefits, see section 6.2. This work initially started without any shape measuring system, shape was measured by visual, and hand measuring (ruler) systems, see section 2.1. As the work progressed an off-line shapemeter was hired [19], section 6.1.

Various avenues have been investigated and findings not initially envisaged as being important have been highlighted. the work has been presented as a series of experiments. Some of the work is completely different in the techniques and methods employed but all concentrate on trying to improve the shape of as-rolled strip. The discussion follows the form of this thesis, but draws on findings throughout.

11.1 MAJOR STRIP SHAPE AFFECTING VARIABLES (section 4).

Strip shape affecting parameters can be broken down into their overall effects on strip shape, or their effect on specific types of strip shape. Initial work in this area was carried out without the use of an off-line shape measuring device. Measurements of shape were taken by a subjective measure of a visual score and description.

The analysis in section 4.2 showed that the position of the fist intermediate rolls is by far the most dominant strip shape affecting parameter. The major strip shape defects are affected by this parameter. The work roll geometry has been shown to have a large effect on strip shape. It is clear that although other parameters do affect strip shape investigational work needed to surround the profiles. Another conclusion from these results is that, with the fist intermediate roll position being so dominant strip position in the mill is important. Any lateral movement of the strip during rolling will adversely affect strip shape.

Lateral strip movement and first intermediate roll position are relative . If the strip moves across the mill it has similar effects on strip shape as altering the first intermediate roll positions.

From the results it is possible to predict the parameters which are dominant to strip shape and also the actions which can reduce these defects, (Appendix 1) Table 10. From the mean response plots the steepest curve shows the most effect and the lowest value shows the best parameter position. The best positions for each parameter with reference to strip shape has been incorporated into a working document, some of the findings of which are shown in Appendix 1.

The tests were carried out on a particular material type, and as such the results may not be completely transferable. However, because of the confirmation with rolling mill operators experience, the author regards the findings as transferrable.

11.2 DETAIL OF THE EFFECTS OF WORK ROLL PARAMETERS ON STRIP SHAPE (Section 5)

Using the Taguchi technique of plotting the results in the form of mean response graphs it was possible to, within the tight constraints of the experiments surrounding work rolls, to place in order the shape affecting parameters on strip shape. The parameter effects are shown in relation to specific strip shape defects. That there are measurable results proves that the work rolls do affect strip shape. From the limited number of parameters tested, the dominant one that affected all of the specific shape defects was the work roll profile. Apart from the fact that work roll geometry is dominant in its affect on strip shape, out of those parameters tested, there are no other clear conclusions. This finding encourages further investigations on strip shape to concentrate on work roll and first intermediate roll geometries.

There are indications from the mean response plots (Figures11-14) that improvements can be made to strip shape. From the trends of the plots the following practices will help to improve strip shape:

a) Use small diameter work rolls.

This seems to be contrary to rolling mill experience which indicated that larger work rolls produce better strip shape. The length of arc of roll contact, lower severity of metal deformation, and ironing effects are reasons given for his. Within normal 4-High and 6-High rolling this will hold true. The special situation of a cluster mill may prove that within the limits of the mill roll cluster, smaller work rolls are better.

An explanation for this proposal is that because horizontal roll bending across which produces poor strip shape, this bending is limited if the work rolls are supported more in the horizontal plane. Smaller work rolls enable such support.

b) Keeping the work rolls the same size.

This practice will help to ensure that the stress distribution laterally through the strip is consistent and symmetrical [11]. General practice is to use different sized rolls for roll re-grinding economics and ease of rolling practice. This work recommends (section 5) a change of practice to keeping rolls in pairs ie: a matched set.

11.3 SADDLE ADJUSTMENTS EFFECTS (Section 6).

The effects of adjusting the saddle setting of a rolling mill have less affect than is often attributed to them. The tests carried out show that, on a narrow mill, saddle adjustments have a minimal affect on strip shape. On a single rolling pass of a sequence on hard 301 HT material the effects of saddle adjustments are not measurable. Investment in any shape control systems which use saddle adjustments alone or as the key shape control parameter should not be made for the mill under test, this recommendation may also hold true for all narrow Sendzimir mills.

Useful and measurable results relating to saddle setting have only been obtained by investigating their effects throughout a complete rolling sequence.

Again, the use of Taguchi experimental design techniques was used to get measurable data. The results from section 6, show that when the saddles are set and held throughout a rolling sequence they have a measurable effect on strip shape. This effect is smaller than that caused by work roll geometry. Saddles affect strip shape independently. Adjusting the saddles affects the loading pattern across the strip so directly affecting strip shape.

If the saddles are set asymmetrically then they will also affect the way in which the strip tends to move laterally across the mill. Any lateral movement of strip across the mill will mean that compensatory, first intermediate roll, movement will need to be used. This will adversely affect strip shape by causing an uneven load and hence differential reductions. The preferred setting of the saddles for specific strip shape defects may be found and incorporated into the recommendations for shape improvement, Appendix 1.

Following from this work are further investigations into the effects of mill parameters through a rolling sequence. This work has proven that rolling parameters, though having an unmeasurable effect on a single rolling pass, do have a cumulative effect on strip shape. Finding the best saddle setting for specific jobs will prove beneficial and help to improve strip shape.

11.4 EFFECTS OF ROLLING PARAMETERS THROUGH A SEQUENCE (Section 7).

Work on saddle adjustment showed that the effects of a parameter on strip shape through a sequence may be more important than is currently appreciated by mill users. The main strip shape affecting parameters for the major strip shape defects are shown to be the first intermediate roll position, work roll profile and saddle settings.

From the results (section 7.5.2) the preferred combinations of settings for each type of strip geometry were found. General observations were also made ie: the rolling tensions should be kept high and the effects of reductions are, within limits, not too critical. This conclusion about reductions takes only the overall reduction into account and does not relate to differences in the final rolling pass which may have a large effect on strip shape.

From analyzing the results (section 7) the best rolling conditions for a specific situation have been found and incorporated into the rolling recommendations, Appendix 1. A significant factor from this work is that the process variability is reduced. Certain parameters such as the tensions and reductions although having a relatively minor effect on shape can have a larger effect on process variability. If the process variability is reduced then a more consistent quality product is produced. Other factors have a large effect on variability but also on shape such as the work roll profile, and the first intermediate roll position. General conclusions can be drawn from reducing process variability which can be transferred on to other jobs ie: lower reductions and high tensions will reduce process variability.

Because of the major effects of the three key rolling parameters of first intermediate roll position, work roll profile and saddle setting, any further work on other specific job types ie: (widths, reductions, material grade, within a range) can be carried out under a smaller series of tests. A Taguchi L9 array which tests three parameters each at three levels can be employed. Only nine tests need to be carried out to find the best rolling conditions. The range of job types within which each set of results is applicable has not yet been found.

11.5 WORK ROLL STRAIN (Section 8 and 9).

This is a new area of work which has not previously been tackled by any other research. The findings provide knowledge of the work roll behaviour which is relevant to strip producers using Sendzimir or cluster mill, and mill designers. The results presented in section 9 show some major findings have been made as to the mode of bending of a work roll when under load. Roll bending is related to specific strip shape defects and some valuable insights have been derived.

New roll profiles were designed and tested based on the information gained (Figure 42f),

First it was shown (section 8.4) that parameters that mostly affect the strains on a work roll were found to be the first intermediate roll position, and the mill load. All other parameters tested showed only slight effects on the roll strains. The measuring technique was either not sensitive enough, or the roll position and mill loads were too dominant to get any results.

Typical strain plots (Figures 27-34) showing how the work rolls bend vertically with resultant affect on the profile of the strip reveal far from symmetrical load patterns. The strains indicate that both between the front and back of the mill, and the top and bottom, there is asymmetry. From this, it is to be expected that the stress pattern forced into the strip will also be asymmetrical and will cause the strip to buckle. There is a severe strain peak shown at one side of the mill, this occurs where the work roll is at the position of contact with the first intermediate roll taper transition. To improve strip shape, it is important that the severity of this peak is reduced.

The first step in re-designing the first intermediate roll profile was to reduce the severity of the taper transition, (Figure 42b). When the first intermediate roll was moved the strain peak and width of its affect was changed. These characteristics were related to knowledge concerning the characteristics of strip shape. A large amount of work roll bending at the mill centre, represented by a large broad strain peak, will cause the "full centre" strip shape defect. A low strain peak towards the edges of the mill represents a loose edge strip shape defect. None of the strain patterns found showed any indication of a gentle roll bending. No matter what the rolling conditions, some degree of strip shape is produced. From the result, a representation of roll bending and its effect on different types of strip shape has been estimated (Figure 39).

The second phase in re-designing a first intermediate roll profile based on this work was to de-sensitise the way a work roll would bend in response to the first intermediate roll position. There is a necessity for a strain peak associated with first intermediate roll taper to enable the strip to be steered during rolling. What is needed, is to stop the peak from enlarging both in magnitude and width due to positional change.

To do this, a roll with a taper for a set distance then levelling off again (Figure 42f) was designed. This, although not exhaustively tested, has initially shown encouraging results. The mill operator successfully rolled strip of good shape, and commented on the fact that large alterations to the first intermediate roll position didn't have the usual large effect on strip shape.

Other observations are that the gradient of the strain peak changes at key first intermediate roll positions (Figures 36 and 37). This gradient change relates to the position of the first intermediate rolls which gives the best strip shape. From this observation, it may be possible to predict the roll position which will give the best opportunity of producing good strip shape. This work would at best be a guide since there are many factors involved during rolling. A more detailed analyzing of the manner with which the gradient alters may provide more useful information that aids re-design of the roll profile.

When the load is increased the values of stains recorded increased dramatically as shown in Figures 36 and 37. The difference between the strain pattern changes due to load and those due to first intermediate roll positional alterations is that, with a load increase, the strain peak does not significantly alter in width. This finding can be related to experience in producing strip shape. Load increases make the strip shape more sensitive to parameters alterations. When rolling using high loads, there is an increased likelihood of producing poor shape, generally that of quarter buckle. A high and narrow pronounced strain peak is likely to produce work roll bending responsible for quarter buckle strip shape. Hard materials are more sensitive to this particular shape defect because of the loads required during rolling.

A key to improving the strip shape is to limit the increase of the strain peak with increasing loads, this can only be done through re-designing roll profile. Rolling so as to reduce the later pass rolling loads will help to reduce strip shape defects. This is general practice at present.

The work on the strain experienced by a work roll due to loading changes can be linked to alterations in load due to speed. One of the difficulties experienced by mill operators is that the strip shape changes due to speed differences during rolling. Because the roller cannot see the strip shape during rolling he has to make some estimate of the changes and compensate for these during setting up. The strip is given a "loose edge" shape defect of varying degrees of severity so that as the load reduces during rolling a good shape is produced. From the results of strains due to load it is possible to estimate the strain difference due to load alterations during rolling. This difference can be related to the strain differences caused by alterations in the first intermediate roll position. A movement of the first intermediate rolls which compensates for these changes can therefore be calculated. If continued this work could lead to a compensation system. The mill operators can set up for good strip shape, then the first intermediate rolls can be moved during rolling based on the compensation calculated from the strain results.

One of the unusual findings from this strain work is that the work rolls appear to bend in the horizontal plane. The roll strains, section 8.4 (also Figure 38), indicate that the top and bottom rolls try to form an "S" shape (Figure 40). When the strains are measured with strip in the mill, this apparent bending is less pronounced but the strain pattern still indicates bending. Strip shape defects relating to strain differences through the strip thickness [10] are thought to be caused by work roll misalignment.

Rolls bending in this manner will cause such differences.

Relating to strip shape, observations have shown that, sometimes centre fullness and always quarter buckle, is accompanied by cross camber and coilset, Table 11. That is shape defects due to overrolling and those due to misalignment occur at the same time. The reason for this is that a high localised pressure shown by the strain peaks, roll bending vertically (Figures 34 and 37), causes over rolling and hence change due to differential reductions. This high pressure also causes the rolls to bend vertically, shown by the horizontal strain results (Figure 38), hence, shape defect due to over rolling and through the thickness stress distribution must occur at the same time. Mill designers are the only ones who can exert some control over this. Preventing horizontal roll bending can perhaps be achieved by better support of the work rolls. Again re-designing of the first intermediate roll along the guidelines already stated will help to reduce horizontal roll bending. Reducing the rolling loads will reduce such bending.

12.0 CONCLUSIONS.

A detailed study was undertaken with the aims of improving the as-rolled stainless steel strip shape. The work has concentrated on one specific rolling mill, that of FZ3 situated at Lee Steel Strip, Meadowhall, Sheffield. The mill is a narrow sendzimir mill. Much of the work and the investigative techniques used can be transferred on to other sendzimir or cluster mills. The control of rolling by means of parameter improvement was investigated. The strip shape affecting parameters were investigated to show their individual magnitude of effects. The effects of the main parameters were then investigated throughout a rolling sequence. The main parameters were further investigated by strain techniques to gain information that would enable improvements to be made to them.

The following conclusions have been drawn:

a) Shape defects in stainless strip have been identified.

b) Taguchi Experimental design techniques can be applied to obtain rolling schedules that separate the parameters which produce specific strip shape defects.

c) The major strip shape affecting parameter is the first intermediate roll position. The effects of other rolling parameters in level of importance are shown Table 10.

d) The importance of correctly aligning the mill and grinding the rolls to a high standard has been highlighted.

e) The parameter settings throughout a rolling sequence, for specific work, which will improve strip shape and produce a more consistent product have been shown.

f) A manual, which will aid mill operators to produce good strip shape has been produced. This incorporates information on the effects of individual parameters and the best settings throughout a sequence. Much of the information in the manual is in Appendix 1.

g) Rolling mill FZ3 produces a typical quarter buckle and loose edge shape defect. That the quarter buckle strip shape is linked to cross camber. That full centre strip shape is linked to cross camber.

h) Sendzimir mill work rolls cross over in the horizontal plane forming an "S" shape. This crossing over of the work rolls occurs at a high pressure point in the roll gap which causes over rolling (full centre or quarter buckle). The crossing of the rolls also accounts for differential stresses in the finished strip through the lateral cross section. These stresses cause cross camber.

i) Analysing the stresses experienced by a work roll is a new technique which can be applied to other mills. The technique may be used to find:

- i) Mill faults.
- ii) Roll bending
- iii) Investigate improvements to roll profiles.
- iv) Relate mill load to first intermediate roll position so finding the best position for the rolls.

v) The amount of compensation by roll movement for mill load changes during rolling can be calculated.

j) New first intermediate roll profiles which de-sensitise the process into these, over powerful, shape affecting parameters have been designed.

k) Without improvements to the first intermediate roll profiles, no position of neutral (perfectly flat) strip shape can be produced.

13.0 SUGGESTIONS FOR FURTHER WORK.

Further work can apply the experimental techniques on the process parameter improvement for production of flat strip on a smaller scale than that used in this investigation. At present, work has been carried out on a grade of material of a specific geometry and reduction, it can also be expanded to other mills and job types.

Work should continue to use work roll strain measurement to estimate the preferred first intermediate roll positions for specific mill set ups. Estimations should be made of the effects of the movement of first intermediate rolls with respect to load differences. This will allow the mill operator to set the mill up on the basis of good shape, not allowing for change of load with speed, but adjusting the first intermediate roll position. This data will be useful in a control system which automatically adjusts the roll position with rolling load changes.

Work roll strain can be extended to measuring the effects of strip tension on roll loading. Difficulties may arise when tensions are applied because the rolls will move and may damage the strain gauges. Comparisons between work with existing models or modified models will prove useful.

Investigations of the bending behaviour of work rolls, and relating this to first intermediate roll profile should continue. Testing roll profiles which desensitise the rolling process to the movement of these rolls will give most benefits to improving strip shape. Knowledge of the horizontal behaviour of rolls will help mill designers and suggest how mills may be designed to prevent horizontal roll bending. If the horizontal roll bending can be controlled then the mill operators will be able to produce good flat strip.

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Table 1. Parameter Description.

Rolling Speed:	Rate at which strip passes through the mill (M/min)
Load:	Force applied to the strip (Tons).
Reduction:	The percentage gauge reduction (%).
Sequence:	Number of reductions and the % reduction of each pass.
Saddles:	Mechanism of adjusting the loading pattern through back-up castor bearings.
Axially Adjustable First Intermediate Rolls:	Profile rolls which can be adjusted to give shape and mill steer control. Typically profiled by a taper at one end.
Work Roll:	The roll in direct contact with the strip. They may be profiled camber to aid strip shape.
Material Quality:	The specific make up of the material being rolled.
Material Profile:	The cross section profile of the supply.
Cooling/Lubrication:	Oil type and amount.
Roll Size:	Diameters of the rolls in the mill.
Front/Back Tensions	High tensions applied to the strip to aid in reduction, steer, and shape control.

Table 2. L16 Orthogonal Array
Used to Assign Parameters for FZ3 Experiments

L16 Array FZ3 Design of experiment

Experiment Number	G	H	B	I	A	I*H	A*H	F	G*F	J	G*J	C	D	E	E*G
1	High	Flat	Flat	In	Shallow	Int 1	Int 1	High	Int 1	High	Int 1	High	Config 1	High	Int 1
2	High	Flat	Flat	In	Shallow	Int 1	Int 1	Low	Int 2	Low	Int 2	Low	Config 2	Low	Int 2
3	High	Flat	Flat	Out	Steep	Int 2	Int 2	High	Int 1	High	Int 1	Low	Config 2	Low	Int 2
4	High	Flat	Flat	Out	Steep	Int 2	Int 2	Low	Int 2	Low	Int 2	High	Config 1	High	Int 1
5	High	Wedge	Camber	In	Shallow	Int 2	Int 2	High	Int 1	Low	Int 2	High	Config 1	Low	Int 2
6	High	Wedge	Camber	In	Shallow	Int 2	Int 2	Low	Int 2	High	Int 1	Low	Config 2	High	Int 1
7	High	Wedge	Camber	Out	Steep	Int 1	Int 1	High	Int 1	Low	Int 2	Low	Config 2	High	Int 1
8	High	Wedge	Camber	Out	Steep	Int 1	Int 1	Low	Int 2	High	Int 1	High	Config 1	Low	Int 2
9	Low	Flat	Camber	In	Steep	Int 1	Int 2	High	Int 2	High	Int 2	High	Config 2	High	Int 2
10	Low	Flat	Camber	In	Steep	Int 1	Int 2	Low	Int 1	Low	Int 1	Low	Config 1	Low	Int 1
11	Low	Flat	Camber	Out	Shallow	Int 2	Int 1	High	Int 2	High	Int 2	Low	Config 1	Low	Int 1
12	Low	Flat	Camber	Out	Shallow	Int 2	Int 1	Low	Int 1	Low	Int 1	High	Config 2	High	Int 2
13	Low	Wedge	Flat	In	Steep	Int 2	Int 1	High	Int 2	Low	Int 1	High	Config 2	Low	Int 1
14	Low	Wedge	Flat	In	Steep	Int 2	Int 1	Low	Int 1	High	Int 2	Low	Config 1	High	Int 2
15	Low	Wedge	Flat	Out	Shallow	Int 1	Int 2	High	Int 2	Low	Int 1	Low	Config 1	High	Int 2
16	Low	Wedge	Flat	Out	Shallow	Int 1	Int 2	Low	Int 1	High	Int 2	High	Config 2	Low	Int 1

A=1st intermediate geometry
B=Work roll geometry
C=speed
D=Back up roll configuration
E=Front tension
F=Back tension
G=Reduction
H=Strip geometry
I=1st intermediate position
J= W.R. Diss Size

A	0.001" per inch 0.002" per inch	Taper Taper	Shallow Steep	E	UTS ¼ UTS	High Low
B	2 Parallel Rolls 2 Cambered Rolls		Flat Camber	F	¼ UTS UTS	High Low
C	100 m/min 70 m/min		High Low	G	20% 10%	High Low
D	Level 5 5 55 Convex 5 2 25		Config 1 Config 2	H	Flat 10% wedge	Flat Wedge
J	1.65-1.7" 1.6"		High Low	I	Roll Full Roll Loose Edge	In) difference Out) ½ inch

Table 3. Relative Effects of Rolling Parameters on Strip Shape According to Visual Appearance.

A.N.O.V.A

Results 1

sum of Squares	parameter	degrees of freedom	mean square	M.S/E.M.S
3.1	G	1	3.1	16.91 **
0.1	H			
0.6	B			
52.6	I	1	52.6	286.9 **
0.1	A			
3.1	I*H	1	3.1	16.91 **
18.1	A*H	1	18.1	98.73 **
0.1	F			
10.6	G*F	1	10.6	57.82 **
14.1	J	1	14.1	76.91 **
3.1	G*J	1	3.1	16.91 **
5.1	C	1	5.1	27.82 **
0.1	D			
1.6	E	1	1.6	8.72 *
0.1	E*G			

pool 6 total of pooled numbers=1.1

E.M.S=error mean square=1.1/6=0.1833

M S/E.M.S=value to compare with "F" tables

F" tables 5% points=5.99
F tables 1% points=13.74

Table 4a. Relative Effects of Rolling Parameters on Strip Shape According to Fullness Results.

A.N.O.V.A

Results 3

sum of squares	perameter	degrees of freedom	mean square	M.S/E.M.S
0.6	G	1	0.6	6 *
0.6	H	1	0.6	6 *
1.6	B	1	1.6	16 **
22.6	I	1	22.6	226 **
0.6	A	1	0.6	6 *
0.6	I*H	1	0.6	6 *
1.6	A*H	1	1.6	16 **
0.1	F	1	0.1	1
0.1	G*F			
0.1	J			
0.1	G*J			
0.1	C			
0.1	D			
0.1	E			
0.1	E*G			

number pooled=7 total of pooled numbers 0.7

E.M.S=0.7/7=0.1

"F"tables 5% points=5.59
"F"tables 1% points=12.25

Table 4b. Relative Effects of Rolling Parameters on Strip Shape According to Quarter Buckle Results.

A.N.O.V.A

Results 5 sum of squares	perameter	degrees of freedom	mean square	M.S/E.M.S
0.3	G	1	0.3	2.31
0	H			
1	B	1	1	7.69 *
0	I			
1	A	1	1	7.69 *
0.3	I*H	1	0.3	2.31
0.3	A*H	1	0.3	2.31
0.3	F	1	0.3	2.31
0.3	G*F			
0	J			
0	G*J			
1	C	1	1	7.69 *
1	D	1	1	7.69 *
0.3	E			
0.3	E*G			

number pooled=7 total of pooled numbers 0.9

E.M.S=0.9/7=0.13

"F"tables 5% points=5.59
"F"tables 1% points=12.25

Table 4c. Relative Effects of Rolling Parameters on Strip Shape According to Ripple (herring-bone) Results.

A.N.O.V.A

Results 4 sum of squares	perameter	degrees of freedom	mean square	M.S/E.M.S
1	G	1	1	5.88 *
0	H			
0.3	B	1	0.3	1.764
12.3	I	1	12.3	72.35 **
1	A	1	1	5.88 *
0	I*H			
0.3	A*H	1	0.3	1.764
0.3	F			
0	G*F			
1	J	1	1	5.88 *
0.3	G*J			
0.3	C			
1	D	1	1	5.88 *
4	E	1	4	23.53 **
0.3	E*G			

number pooled=7 total of pooled numbers 1.2

E.M.S=1.2/7=0.17

"F"tables 5% points=5.59

"F"tables 1% points=12.25

Table 4d. Relative Effects of Rolling Parameters on Strip Shape According to Edge Wave Results.

A.N.O.V.A

Results 2 sum of squares	pdrameter	degrees of freedom	mean square	M.S/E.M.S
0	G			
1	H	1	1	16.66 **
2.3	B	1	2.3	38.33 **
12.3	I	1	12.3	205 **
0	A			
1	I*H	1	1	16.6 **
2.3	A*H	1	2.3	38.3 **
0.3	F	1	0.3	5
0	G*F			
1	J	1	1	16.6 **
0.3	G*J	1	0.3	5
0.3	C	1	0.3	5
0	D			
1	E	1	1	16.6 **
0.3	E*G			

number pooled=5 total of pooled numbers=0.3

E.M.S=0.3/5=0.06

F"tables 5% points=6.61
F"tablés 1% points=16.26

Table 5. Relative Effects of Rolling Parameters on Strip Shape According to Profile Difference.

A.N.O.V.A

Results 7

sum of squares	perameter	degrees of freedom	mean square	M.S/E.M.S
0.3	G			
289	H	1	289	259.4 **
2.3	B			
16	I	1	16	14.36 **
2.3	A			
4	I*H	1	4	3.59
0.3	A*H			
0	F			
2.3	G*F			
9	J	1	9	8.07 *
0.3	G*J			
25	C	1	25	22.44 **
6.3	D	1	6.3	5.65 *
4	E	1	4	3.59
20.3	E*G	1	20.3	18.22 **

number pooled=7 total of number pooled= 7.8

E.M.S=7.8/7=1.114

"F"tables 5% points=5.59
"F"tables 1% points=12.25

Table 6. Work Roll Parameters Tested and Their Settings.

A	Work Roll Diameter.	Small (1.8).	Large (1.7).
B	Roll Configuration.	Same. (Both same size).	Different. (Small and Large).
C	Interaction.	Initially chosen as pass line height but changed to interaction because the pass line could not be altered.	
D	Tensions.	High 5670 KG	Low 3400 KG
E	Gauage Control.	On.	Off.
F	Roll Geometry.	Flat Rolls.	Cambered Rolls.
G	No Parameters.		

Table 7. Parameters Tested for Assessing the Effects of Saddle Adjustments and Work Rolls on Strip Shape.

A	Saddles.	High Centre Load.	High Edge Load.
B	Work Rolls.	Cambered.	Flat

Table 8. Parameters Tested and and Levels for Assessing the Effects of Rolling Parameters Throughout a Rolling Sequence.

	Parameters.	Levels.			
A	Work roll configuration.	2 Flat	2 Camber	1 Flat 1 Camber	2 Flat
B	First intermediate roll position.	Aim Loose Edge.	Aim Full Centre.	Aim Flat.	Aim Flat.
C	Saddle settings.	Level 5555	convex 2552	concave 8558	taper 2345
D	First intermediate roll taper geometry.	Single.	Single.	Double.	Double.
E	Speed.	high 100m/min	high 100m/min	low 80m/min	low 80m/min
F	Reductions	6 passes.	6 passes.	8 passes.	8 passes.
G	Rolling mill operators.	No 1	No 1	No 2	No 2
H	Tensions.(Kg)	high 7900	high 7900	low 5700	low 5700

Table 9a. Through the Rolling Sequence.

A.N.O.V.A of the full centre measuring method

Parameter	D.of.F	S.of.S	V	F	Significance
A	3	6.63	2.21	11.6	*
B	3	18.18	6.06	31.9	**
C	3	2.9	0.97	5.1	
D	1	0.1	0.1		
E	1	1.9	1.9	10	*
F	1	2.33	2.33	12.2	*
G	1	0.47	0.47		
H	1	4.34	4.34	22.8	*
I	1	0	0		

D.of.F=Degrees of freedom
S.of.S=Sum of squares
V=Variance
F=No to compare with F tables
*=95% Confidence
Pooled 3

Table 9b. Through the Rolling Sequence.

A.N.O.V.A of theloose edge measuring method

Parameter	D.of.F	S.of.S	V	F	Significance
A	3	1.58	0.52		
B	3	31.43	10.48	23.2	*
C	3	18.9	6.3	14	
D	1	3.1	3.1	6.9	
E	1	0.38	0.38		
F	1	5.6	5.6	12.4	
G	1	2.4	2.4	5.3	
H	1	3.21	3.21	7.1	
I	1	8.02	8.02	17.8	

D.of.F=Degrees of freedom
S.of.S=Sum of squares
V=Variance
F=No to compare with F tables
*=95% Confidence
Pooled 2

A.N.O.V.A of the average measuring method

Parameter	D.of.F	S.of.S	V	F	Significance
A	3	3.58	1.2	17.14	*
B	3	2.36	0.8	11.4	*
C	3	0.68	0.22		
D	1	0			
E	1	0.43	0.43	6.14	
F	1	0			
G	1	1.09	1.09	15.6	*
H	1	0.68	0.68	9.7	
I	1	0.57	0.57	8.14	

D.of.F=Degrees of freedom
S.of.S=Sum of squares
V=Variance
F=No to compare with F tables
*=95% Confidence
Pooled 2

Table 9d. Through the Rolling Sequence.

A.N.O.V.A of the Signal to noise ratio

Parameter	D.of.F	S.of.S	V	F	Significance
A	3	123	41	45.56	*
B	3	83.53	27.84	30.93	*
C	3	31.53	10.51	12.12	
D	1	1.37	1.37		
E	1	6.79	6.79	7.54	
F	1	0.43	0.43		
G	1	16.63	16.63	18.48	*
H	1	31.12	31.12	34.58	*
I	1	13.23	13.32	14.72	

D.of.F=Degrees of freedom
S.of.S=Sum of squares
V=Variance
F=No to compare with F tables
*=95% Confidence
Pooled 2

Table 10. Parameter settings to Reduce Strip Shape Defects and Process Variability.

The order of significance of, and settings of parameters to reduce the full centre strip shape defect.

Parameter	Order of Significance	Best Setting	Worst Setting
Taper position	1	Aim good shape	Aim loose
Work roll configuration	2	One flat and one camber	Two flat
Saddle settings	3	Concave	Even, convex, and tapered
Tensions	5	Low	High
Speed	5	Slow	Fast
Reductions	6	6 pass	8 pass
Taper geometry	8	Single taper	Double taper
Rollers	8	No1	No2

The order of significance and settings of parameters to reduce loose edge strip shape defect.

Parameter	Order of Significance	Best Setting	Worst Setting
Taper position	1	Aim full centre	Aim loose edge
Work roll configuration	2	One flat and one camber	Two flat and two cambered
Rollers	4	No2	No1
Tensions	4	High	Low
Speed	6	Slow	Fast
Saddle settings	6	Tapered	Concave, convex, level
Taper geometry	-	---	---

The order of significance of and settings of parameters to reduce average value strip shape.

Parameter	Order of Significance	Best Setting	Worst Setting
Work roll configuration	1	Two cambered	One flat and one cambered
Taper position	2	Aim full shape	Aim good shape
Saddle settings	8	Taper	Concave
Tensions	8	High	Low
Speed	8	Fast	Slow
Reductions	8	8 pass	6 pass
Taper geometry	8	Single taper	Double taper
Rollers	8	No2	No1

Table 11 Typical Shape Measurements and Observations Showing That Strip Shape With Fullness/Quater Buckle aslo Exhibits Coilset.

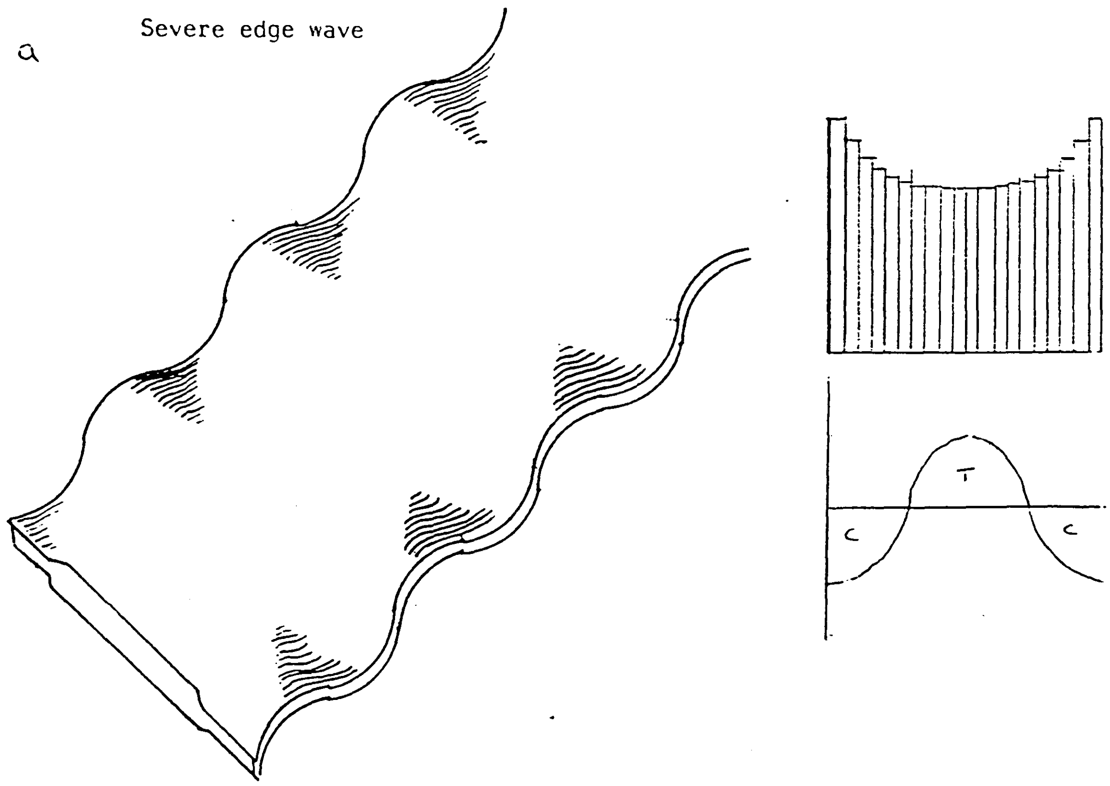
Folio No	Qual	Gauge	Width	Coilset	
				L	U
11476/11	304	0.0136"	12"	41 mm	5 mm
10381/11	304	0.0124"	12"	178 mm	10 mm
11620	301 HT	0.012"	16.125"	50 mm	----
11486/11	301 HT	0.015"	17"	150 mm	42 mm
11012/11	301	0.0039"	8"	6 mm	----

Folio No	Wave		Cross camber	Comments
	Length	Height		
11476/11	370 mm	5 mm	----	1/4 Buckle and loose edge
10381/11	450 mm	10 mm	14 mm	Full centre coilset
11620	-----	-----	6 mm	Slight 1/4 buckle
11486/11	330 mm	8 mm	10 mm	Full centre coilset and cross camber
11012/11	140 mm	1 mm	-----	Slight 1/4 buckle

Figure 1a-d.
Typical Strip Shape Defects Produced by Differential Reductions With Thier Associated Stress Patterns.

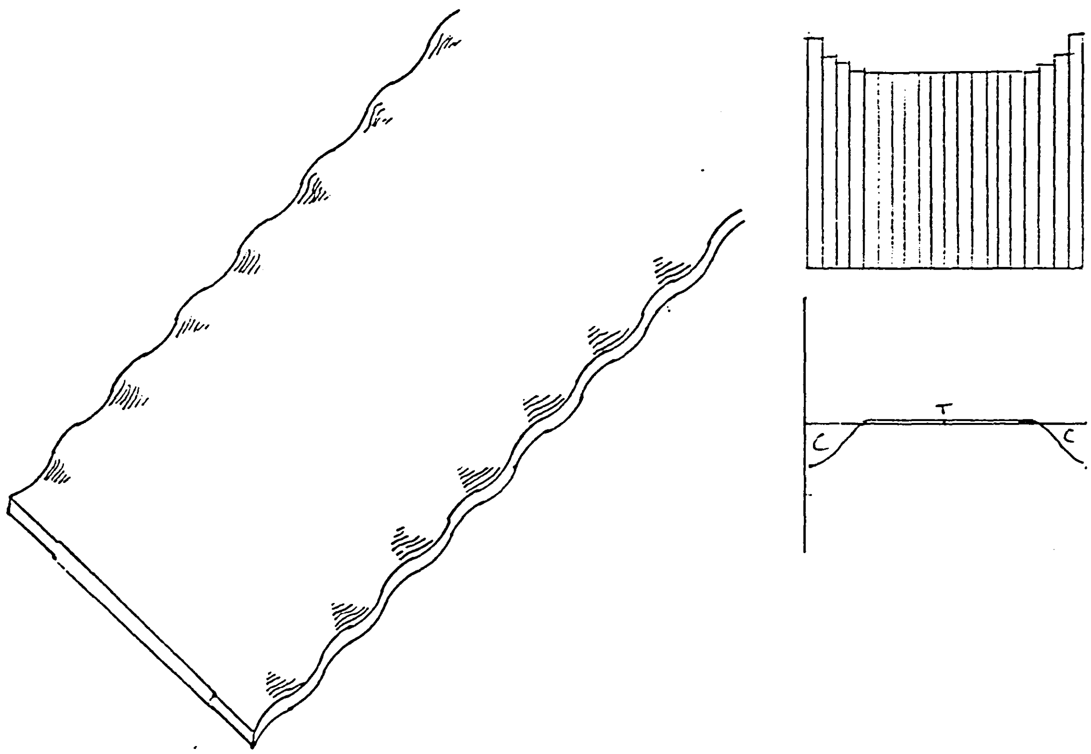
a

Severe edge wave



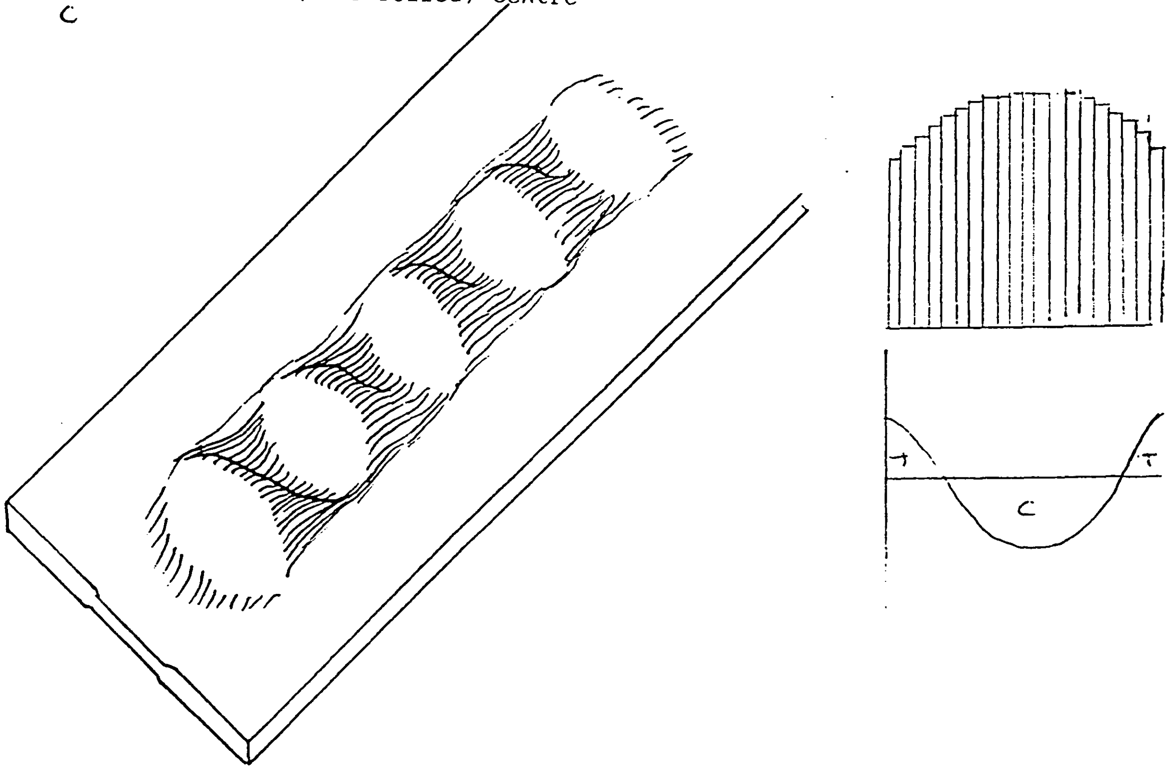
b

Edge wave



c

Full (over rolled) centre



d

Quarter buckle

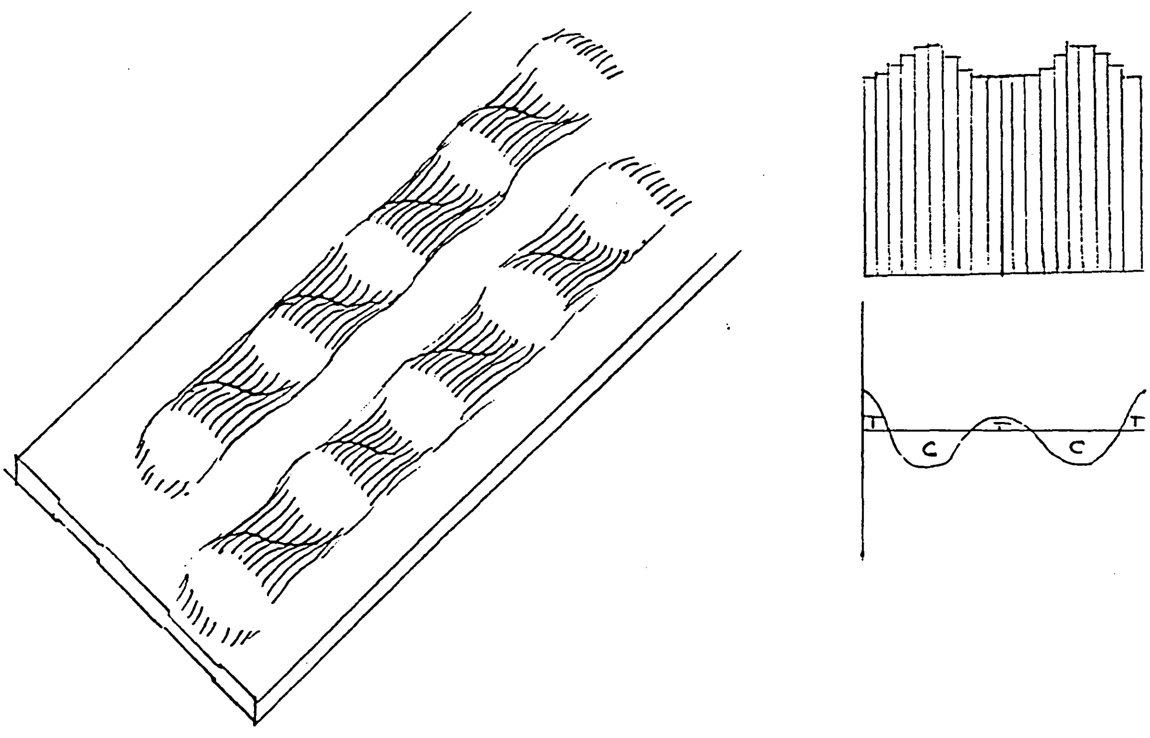
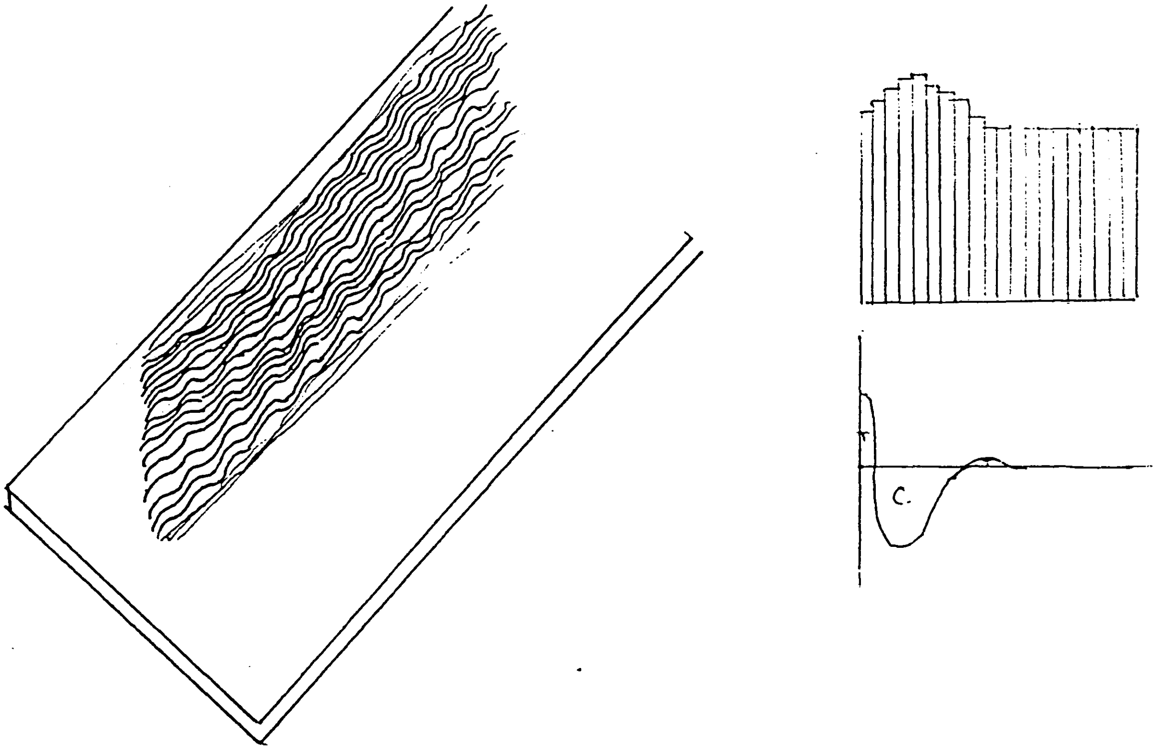
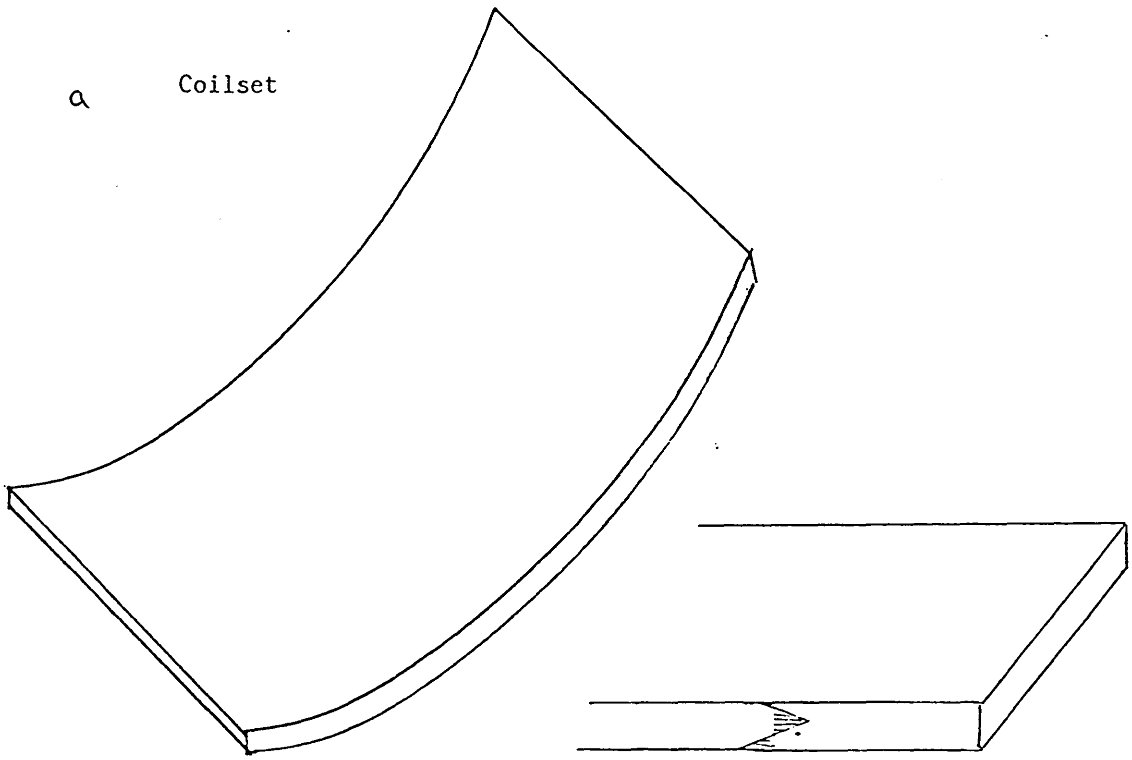


Figure 2a-c.
Typical strip Shape Defects Produced by Through the Thickness Stress Differentials.

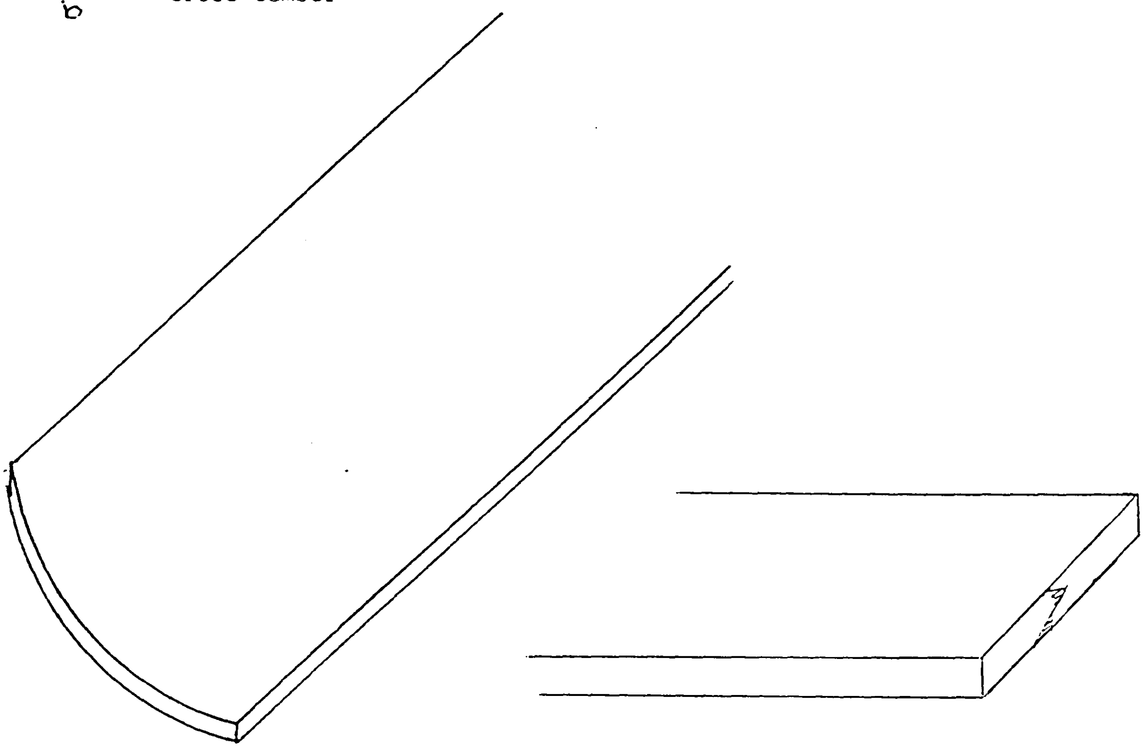
e Herring bone (ripple)



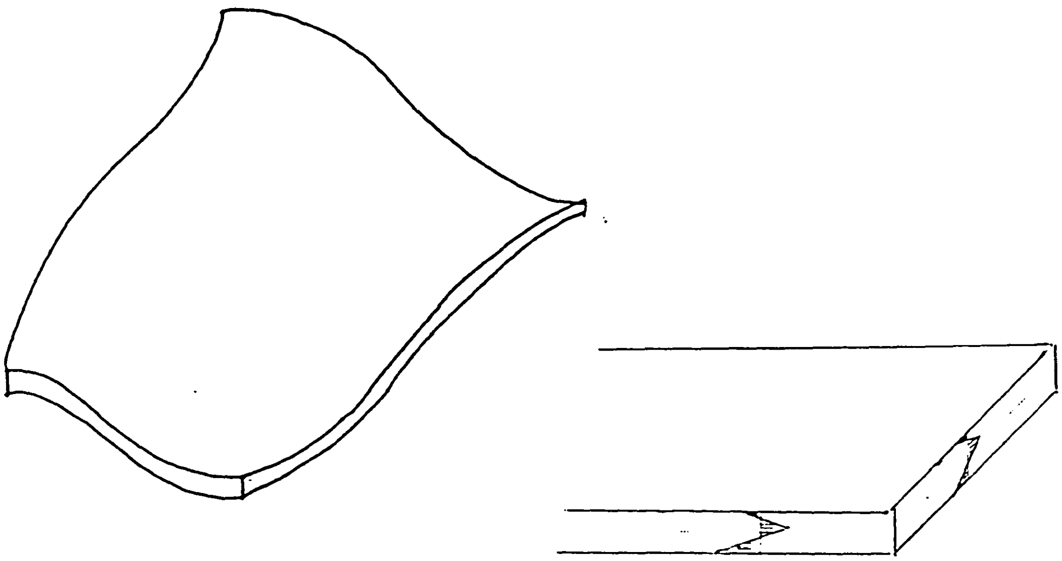
a Coilset

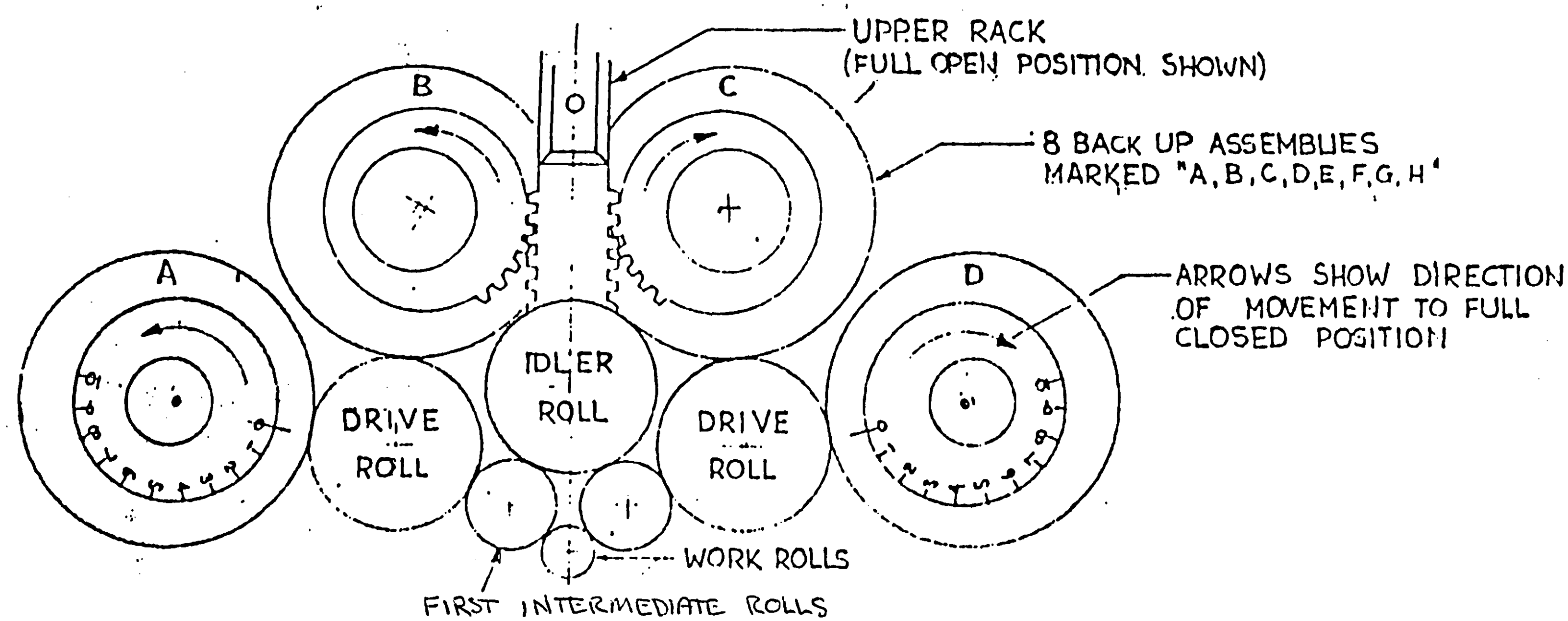


b Cross camber



c Twist




UPPER RACK
(FULL OPEN POSITION. SHOWN)
8 BACK UP ASSEMBLIES
MARKED "A, B, C, D, E, F, G, H"
ARROWS SHOW DIRECTION
OF MOVEMENT TO FULL
CLOSED POSITION
A
B
C
D
DRIVE ROLL
IDLER ROLL
DRIVE ROLL
WORK ROLLS
FIRST INTERMEDIATE ROLLS

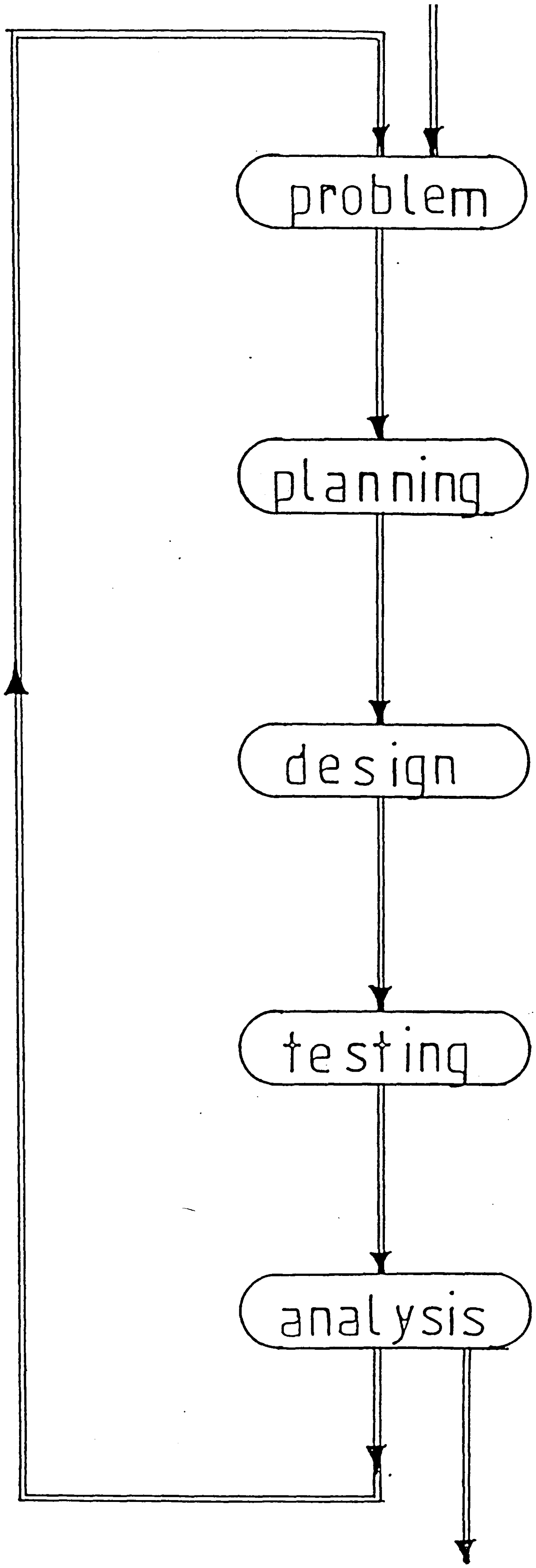
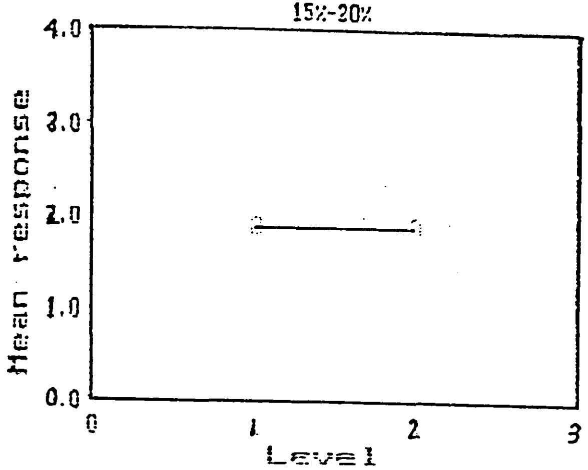
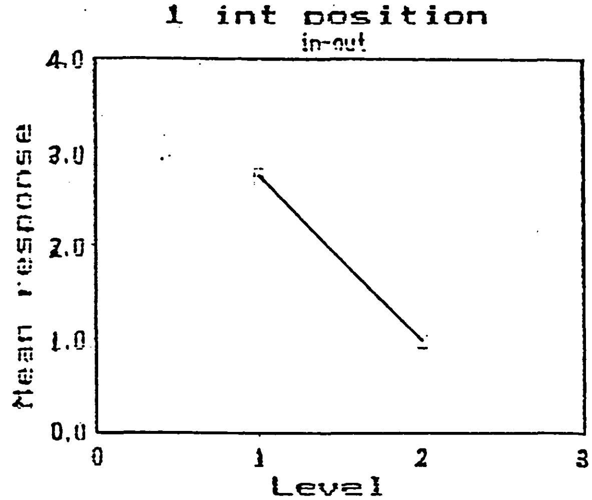
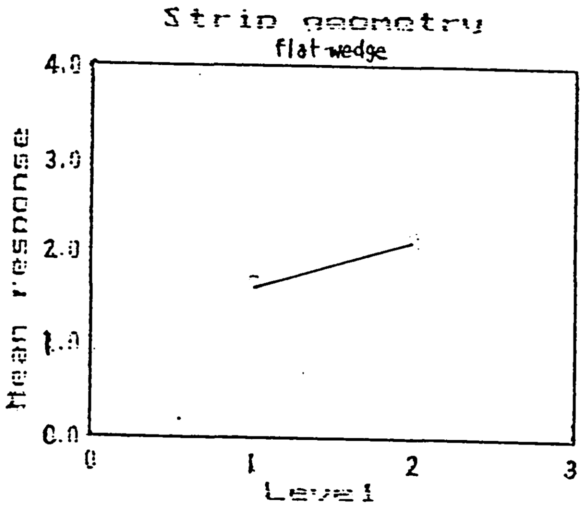
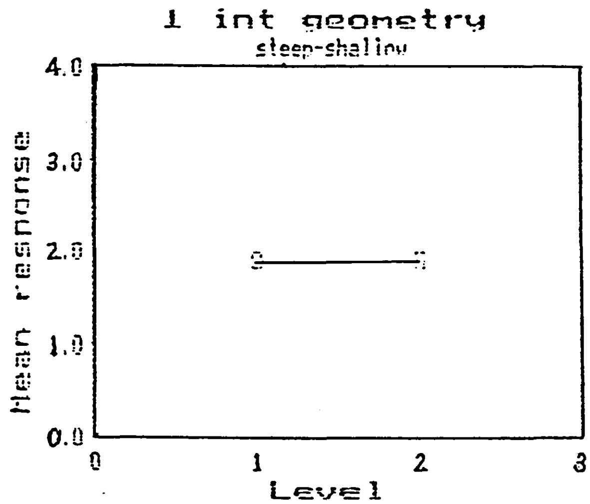

problem
planning
design
testing
analysis

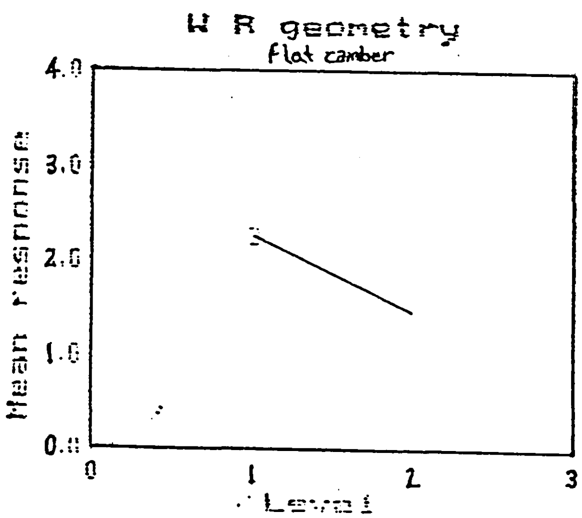
Figure 5.
Mean Response Plots and Results for the Edge Wave Strip Shape Defect, from a Single Part of a Rolling Sequence.

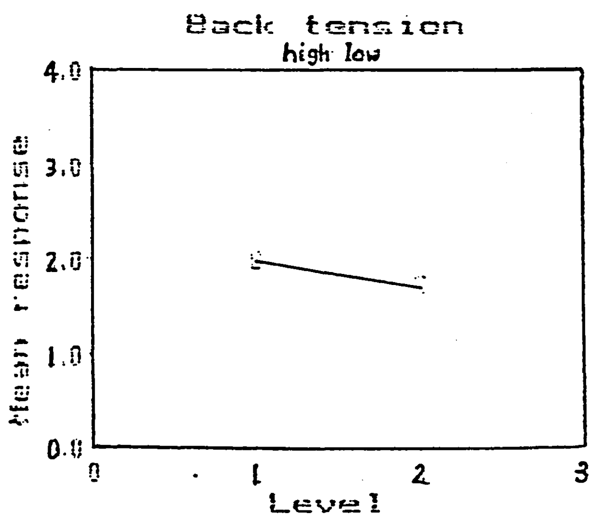

15%-20%
Mean response
Level


1 int position
in-out
Mean response
Level


Strip geometry
flat-wedge
Mean response
Level

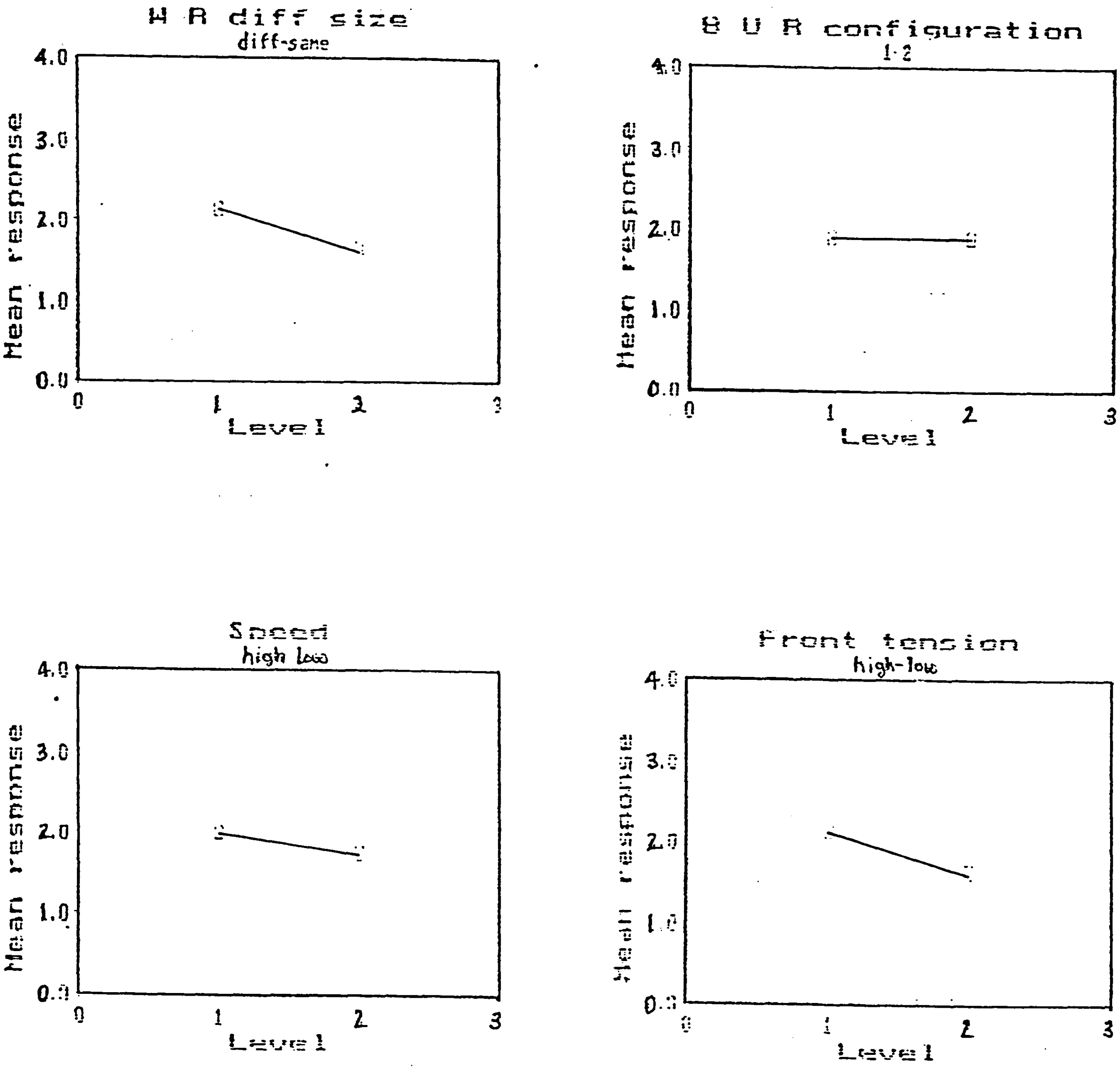

1 int geometry
steep-shallow
Mean response
Level


W R geometry
flat camber
Mean response
Level

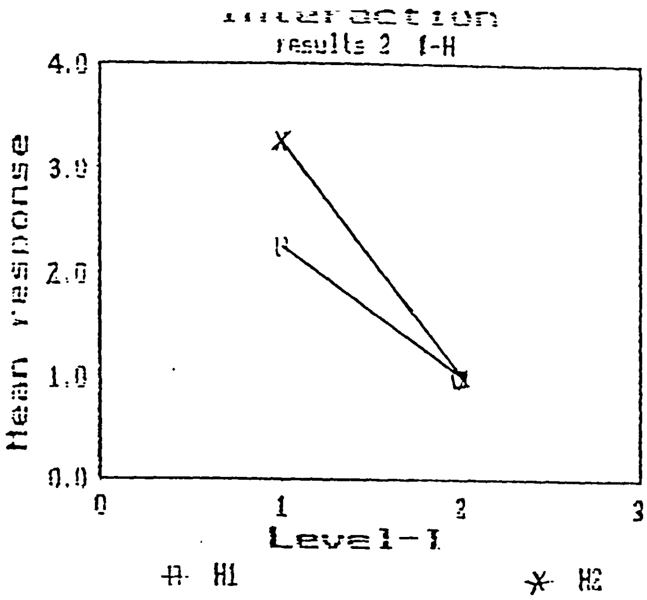

Back tension
high low
Mean response
Level

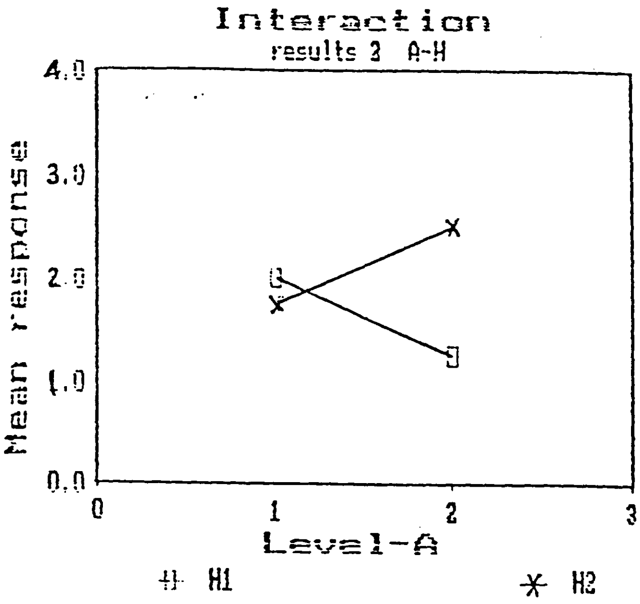
Edge wave 0-4

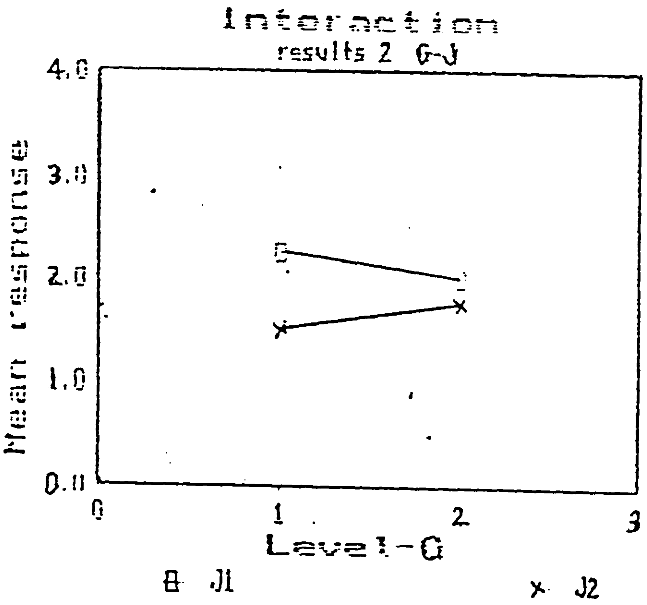
b

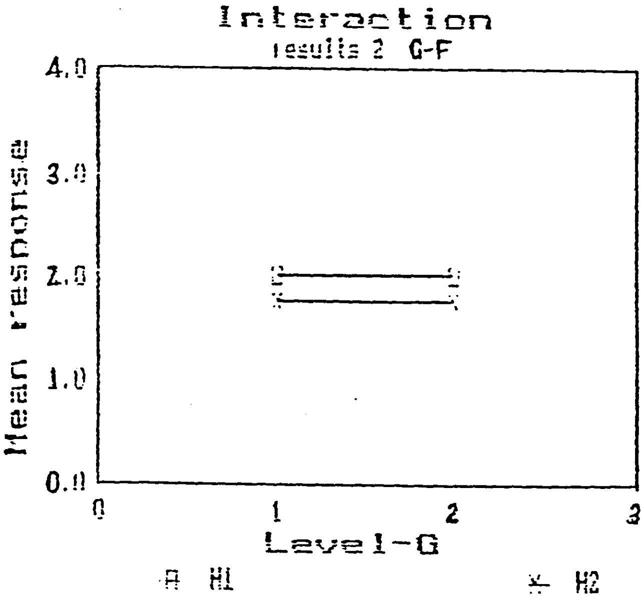


Edge wave 0-4.


Interaction
results 2 I-H
4.0
3.0
2.0
1.0
0.0
Mean response
0
1
2
3
Level-I
H1
H2


Interaction
results 3 A-H
4.0
3.0
2.0
1.0
0.0
Mean response
0
1
2
3
Level-A
H1
H2


Interaction
results 2 G-J
4.0
3.0
2.0
1.0
0.0
Mean response
0
1
2
3
Level-G
J1
J2


Interaction
results 2 G-F
4.0
3.0
2.0
1.0
0.0
Mean response
0
1
2
3
Level-G
H1
H2

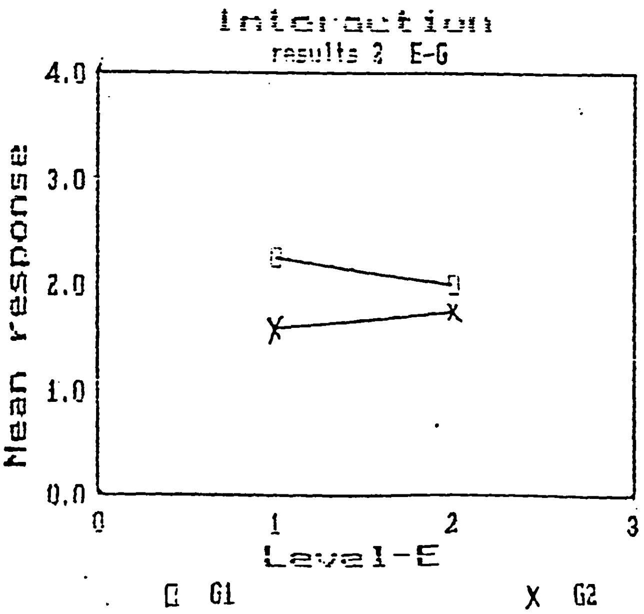
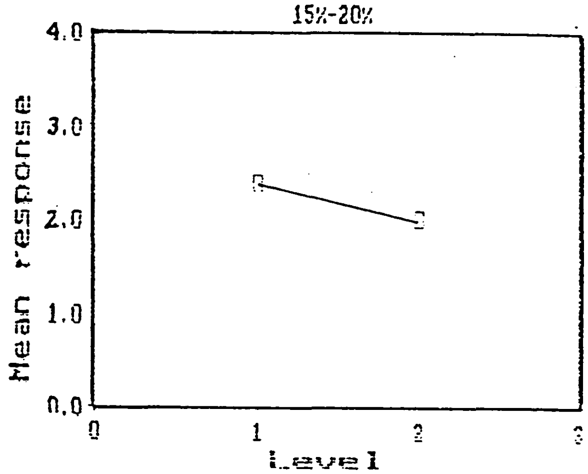
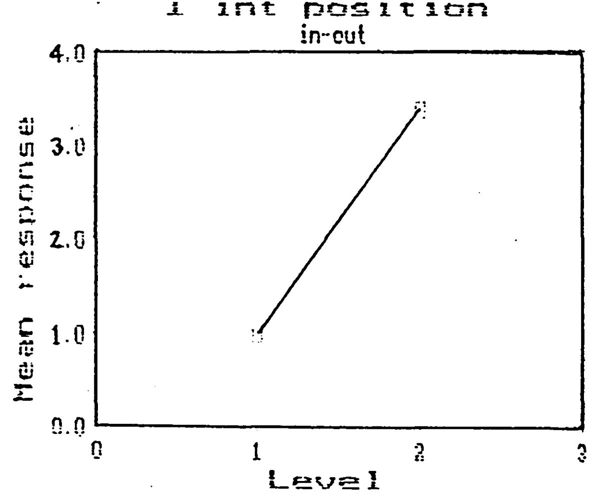
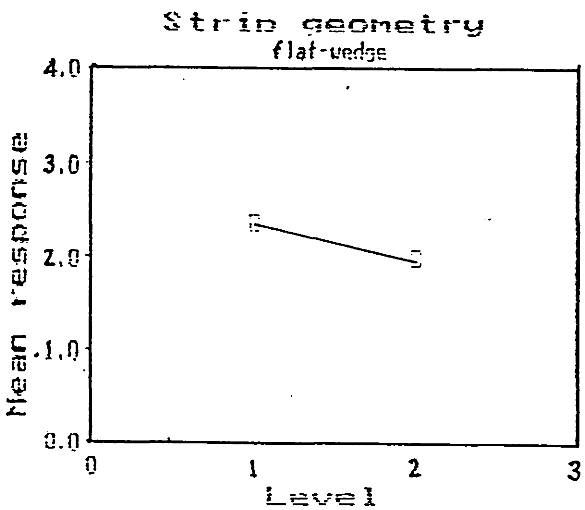
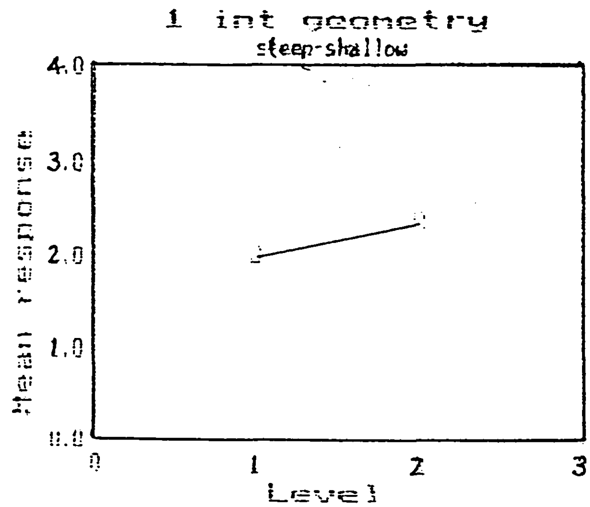

Interaction
results 2 E-G
4.0
3.0
2.0
1.0
0.0
Mean response
0
1
2
3
Level-E
G1
G2

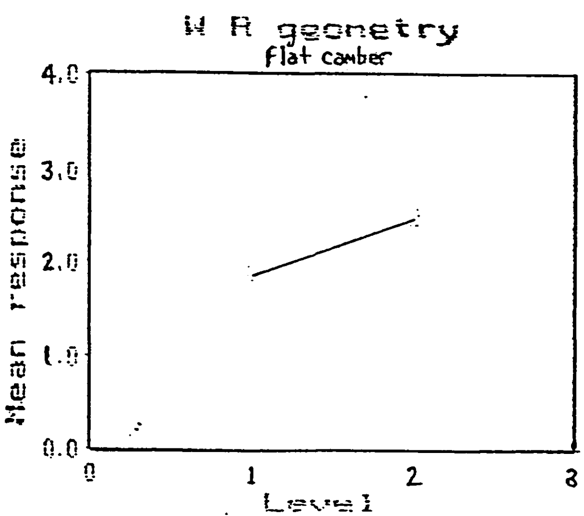
Figure 6.
Mean Response Plots and Results for the Full Centre Strip Shape Defect, from a Single Part of a Rolling Sequence.

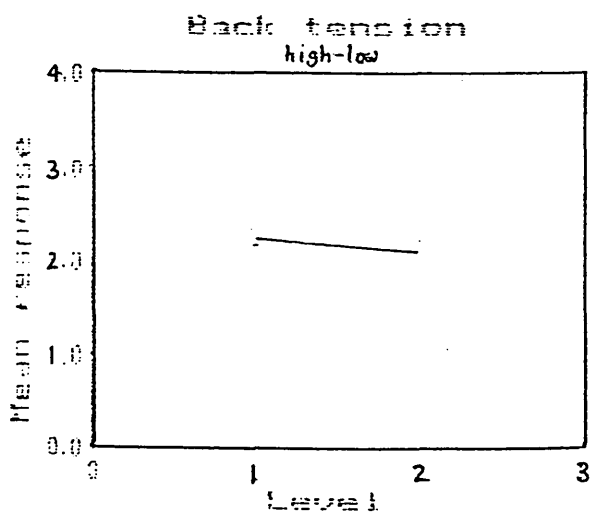

15%-20%
Mean response
Level


in-out
Mean response
Level


Strip geometry
flat-wedge
Mean response
Level

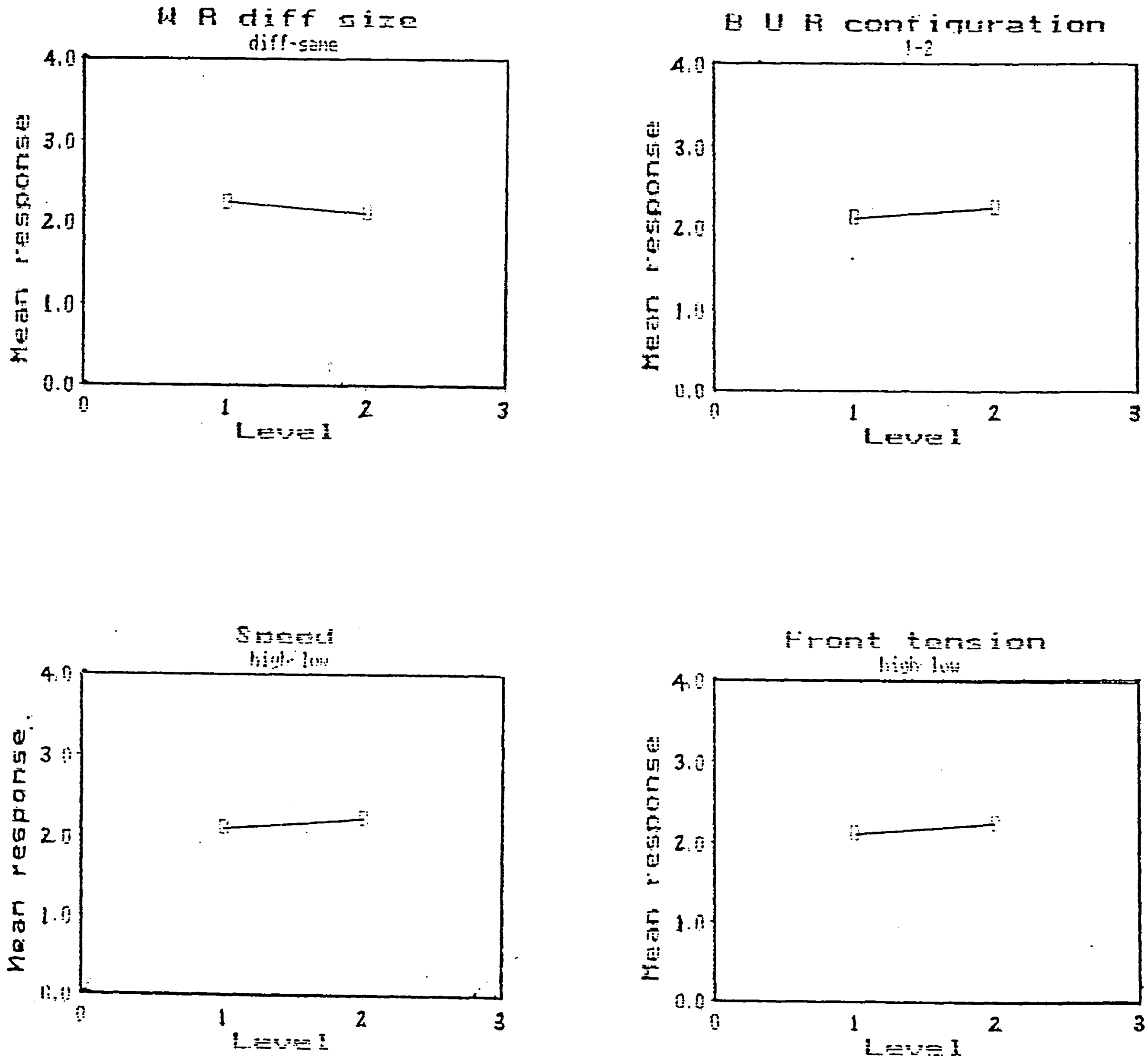

int geometry
steep-shallow
Mean response
Level


W R geometry
Flat camber
Mean response
Level


Back tension
high-low
Mean response
Level

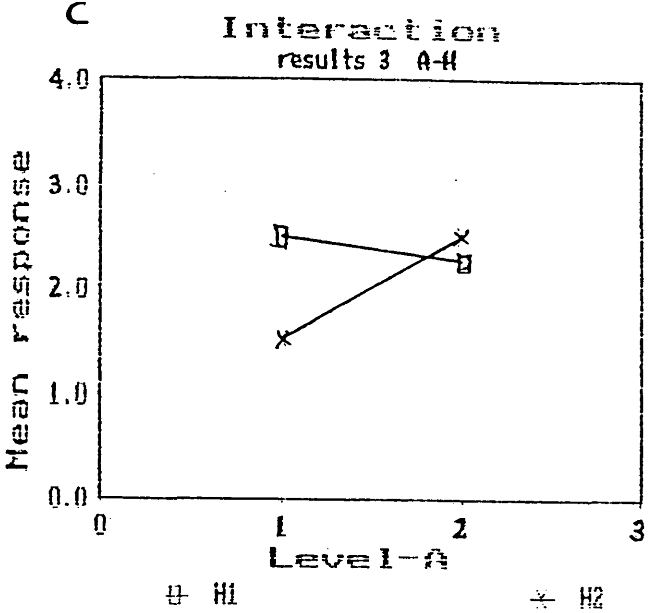
Fullness 0-4

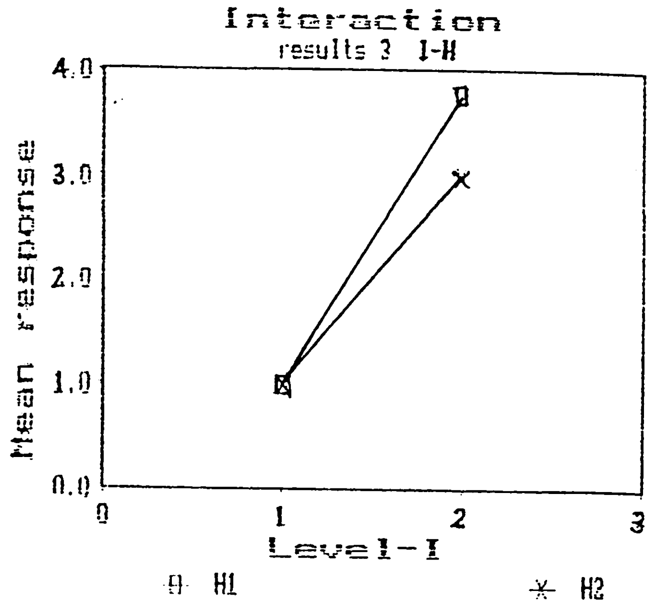
b

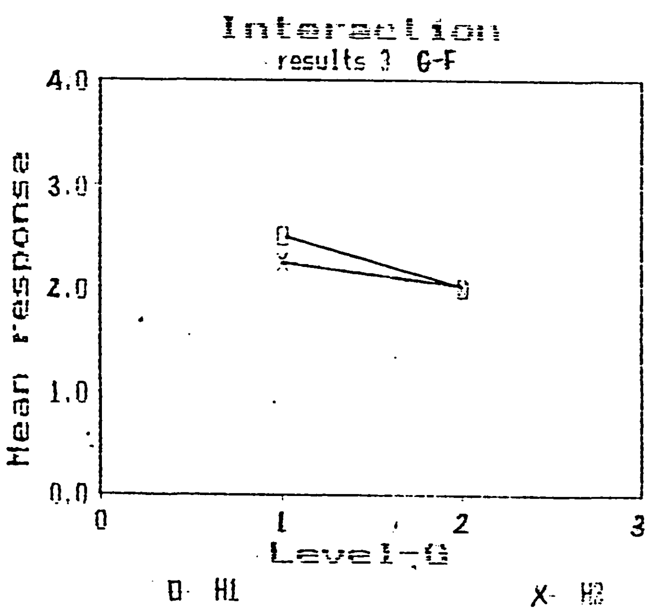


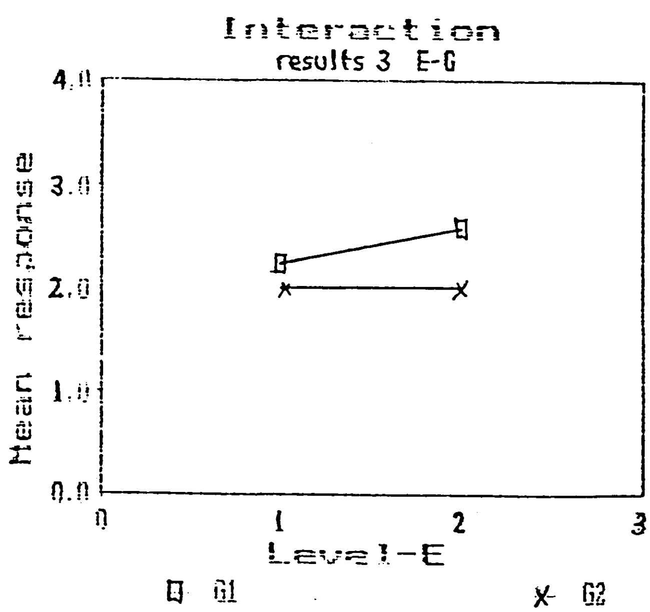
Fullness 0-4

C


Interaction
results 3 A-H
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-A
H1
H2


Interaction
results 3 I-H
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-I
H1
H2


Interaction
results 3 G-F
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-G
H1
H2


Interaction
results 3 E-G
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-E
G1
G2

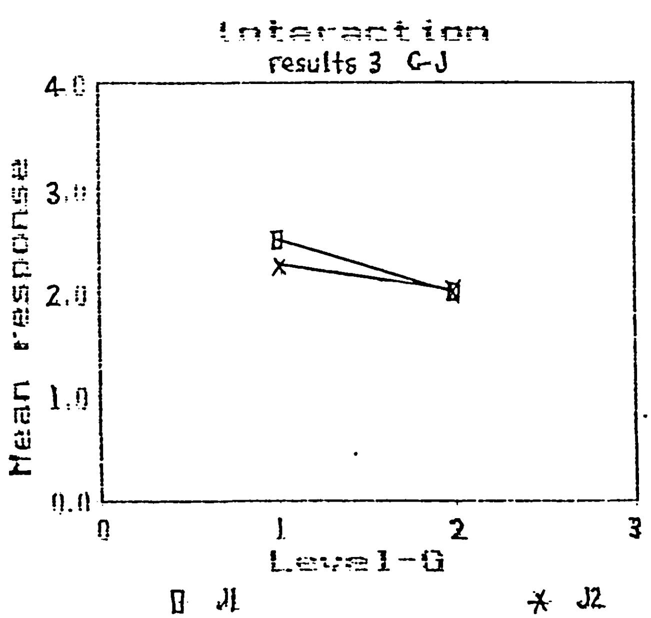
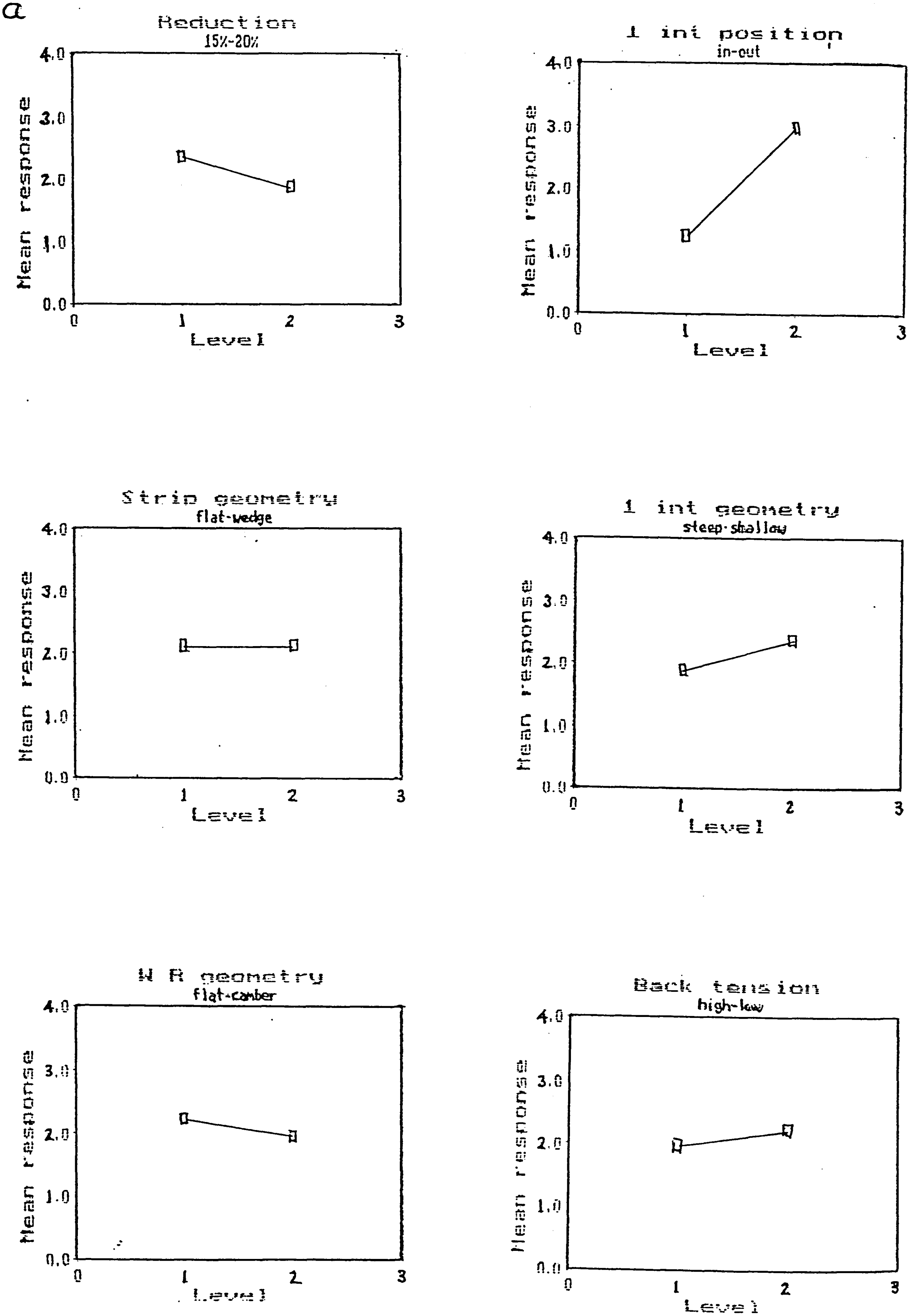

Interaction
results 3 G-J
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-G
J1
J2

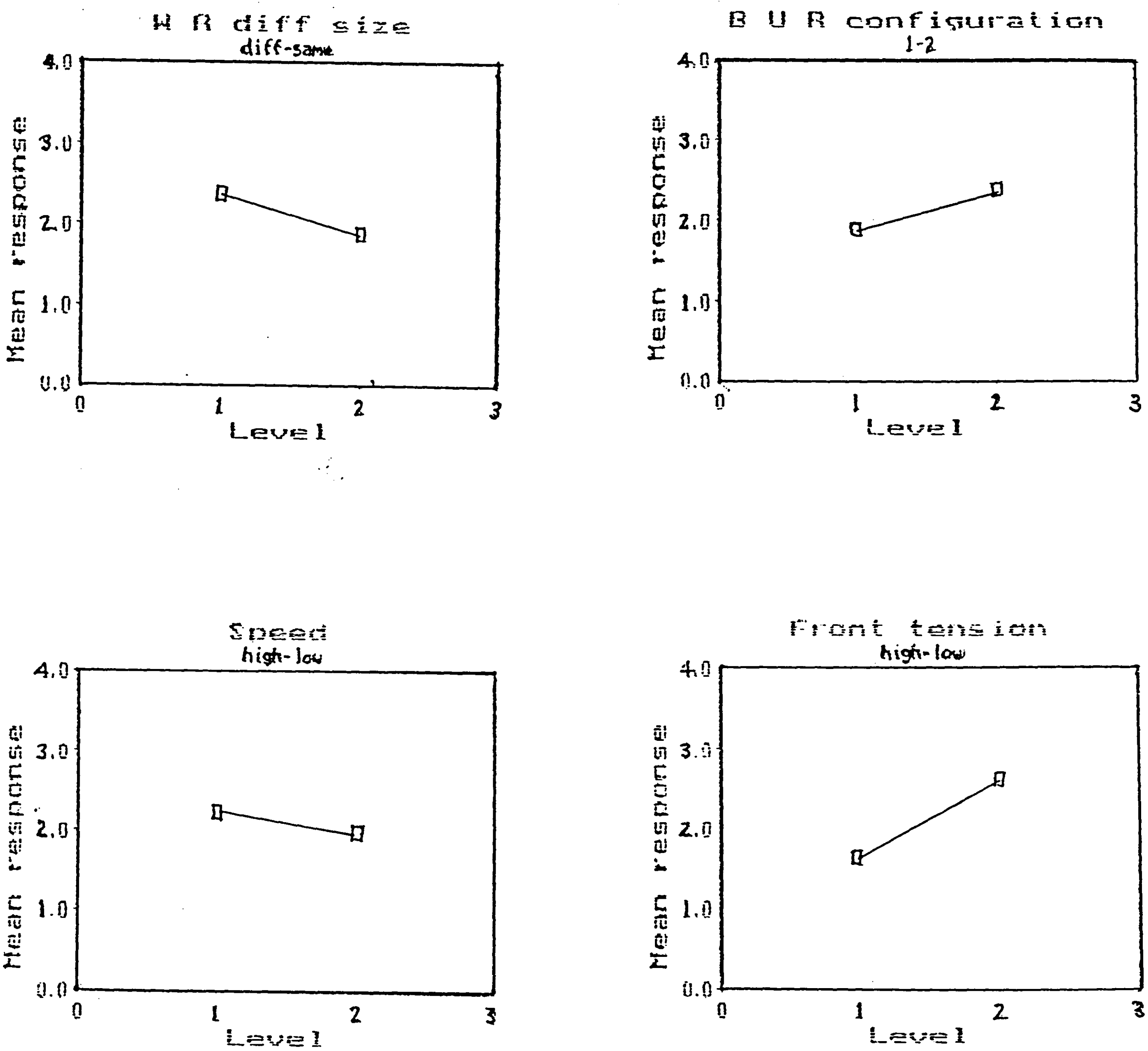
Figure 7.
Mean Response Plots and Results for the Ripple (herring-bone) Strip Shape defect, from a Single Part of a Rolling Sequence.

a

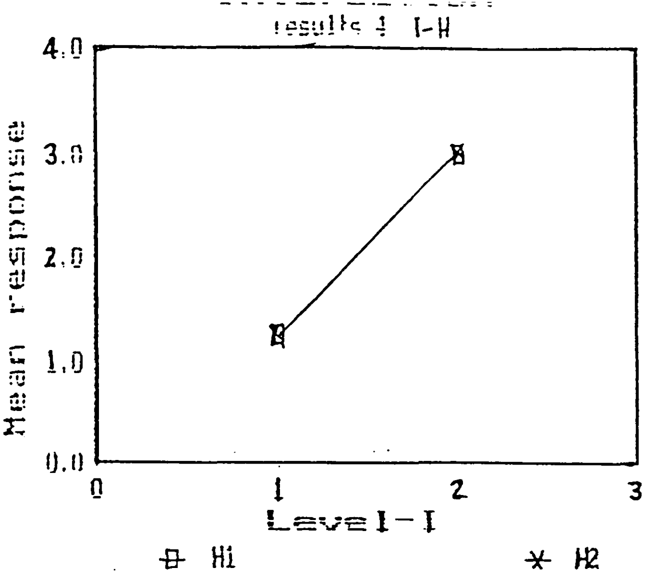


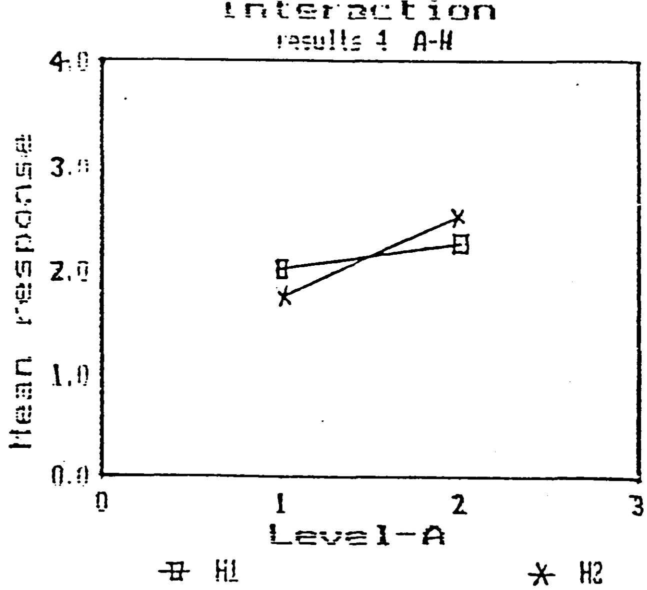
Reduction
15%-20%
1 int position
in-out
Strip geometry
flat-wedge
1 int geometry
steep-shallow
W R geometry
flat-camber
Back tension
high-low
Mean response
Level
0.0
1.0
2.0
3.0
4.0
0
1
2
3

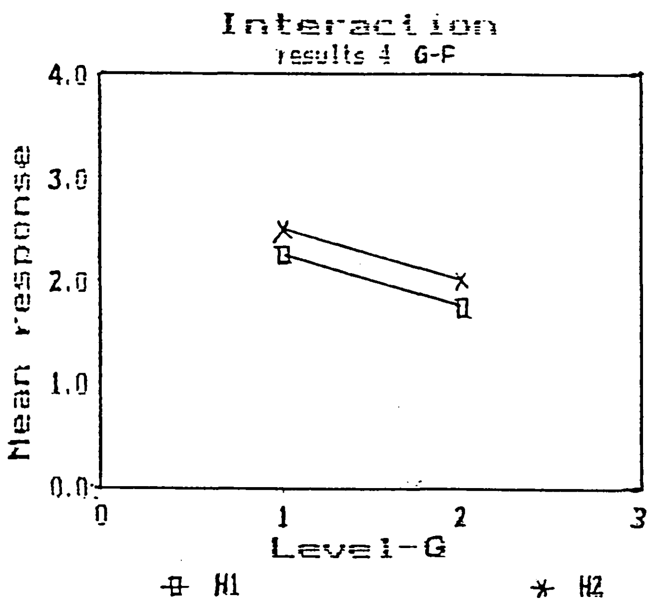
b

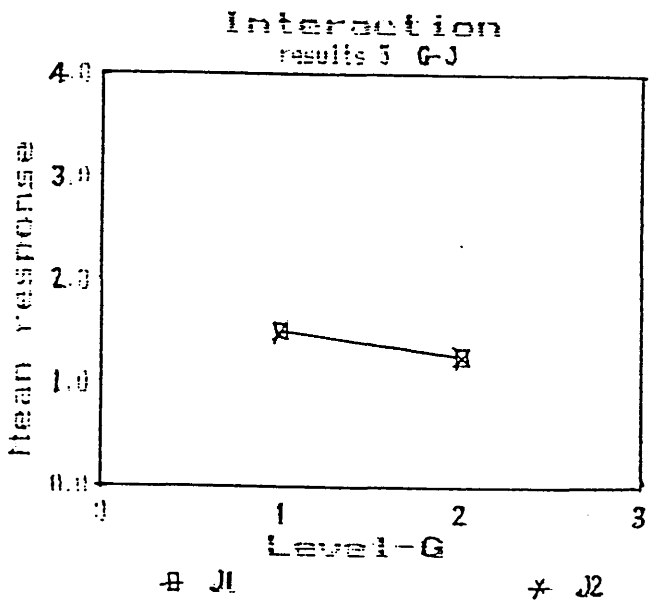

W R diff size
diff-same
B U R configuration
1-2
Speed
high-low
Front tension
high-low
Mean response
Level
0.0
1.0
2.0
3.0
4.0
0
1
2
3

Ripple 0-4.


results 4 I-H
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-I
H1
H2


Interaction
results 4 A-H
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-A
H1
H2


Interaction
results 4 G-F
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-G
H1
H2


Interaction
results 3 G-J
Mean response
4.0
3.0
2.0
1.0
0.0
1
2
3
Level-G
J1
J2

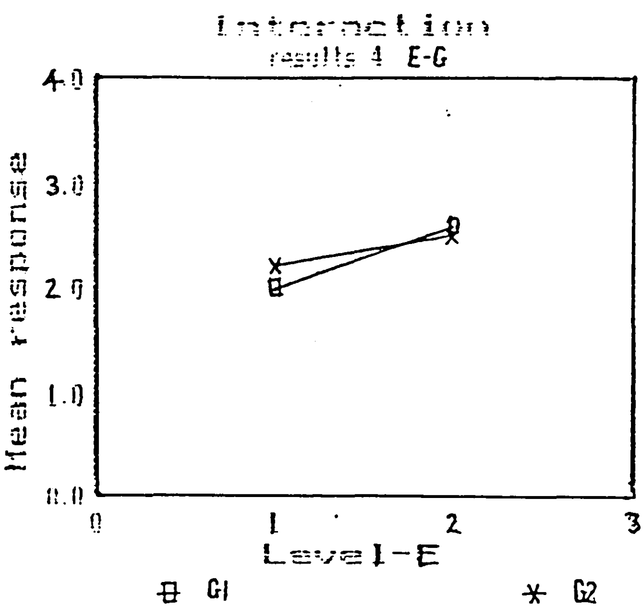
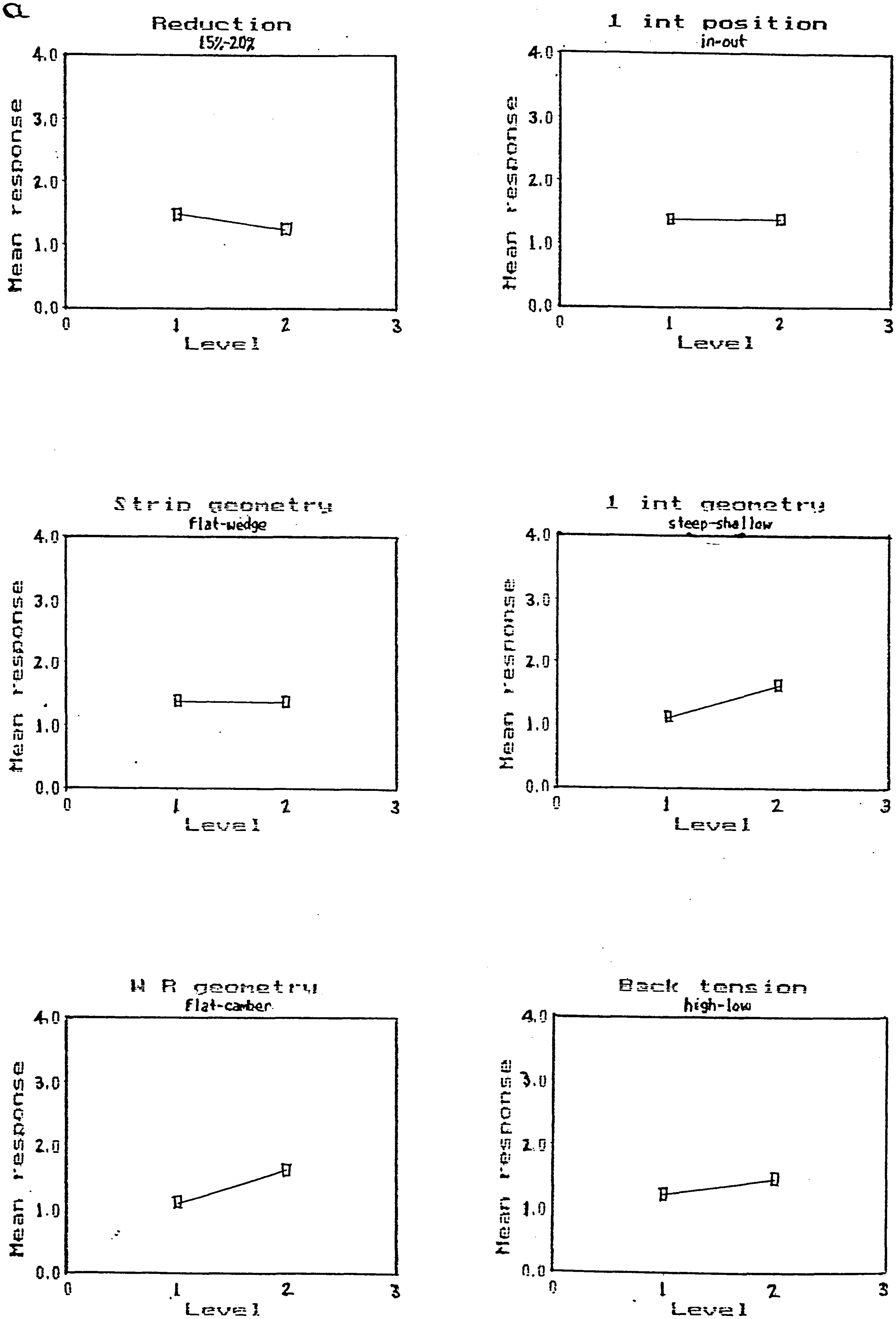

Interaction
results 4 E-G
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-E
G1
G2

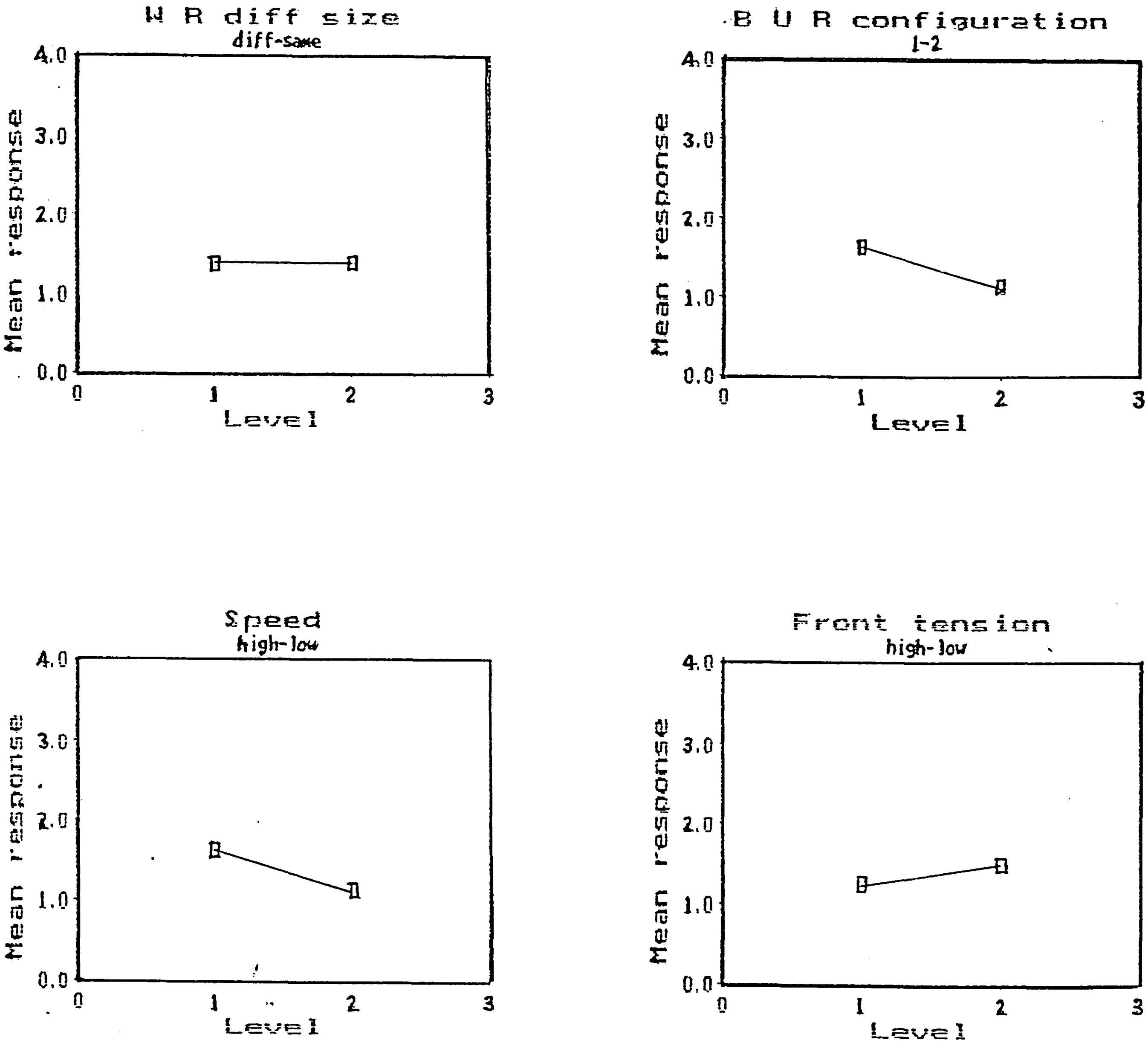
Figure 8.
Mean Response Plots and Results for the Quarter Buckle Strip Shape Defect, from a Single Part of a Rolling Sequence.

a



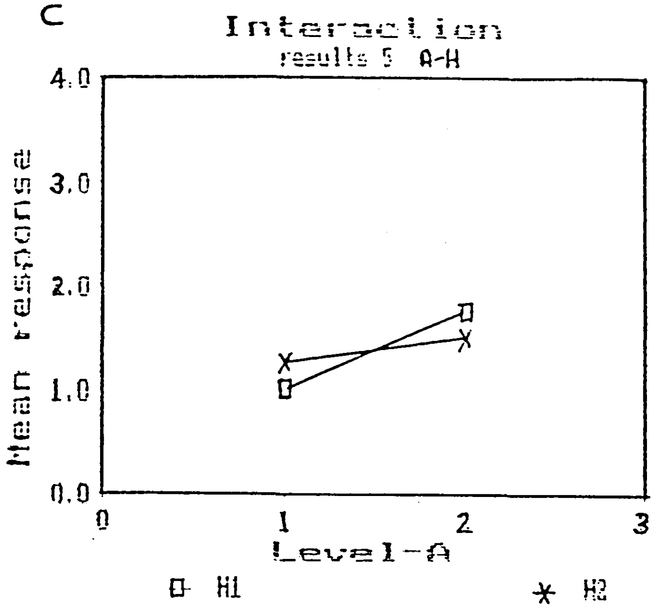
1/4 buckle 0-4

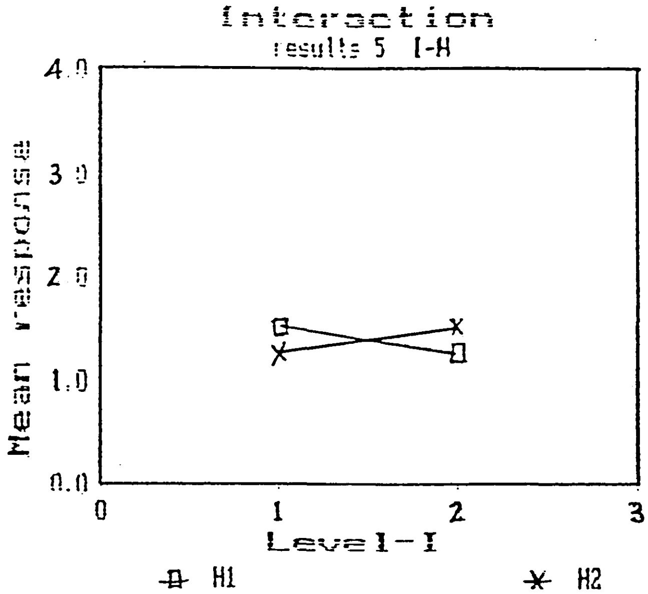
b

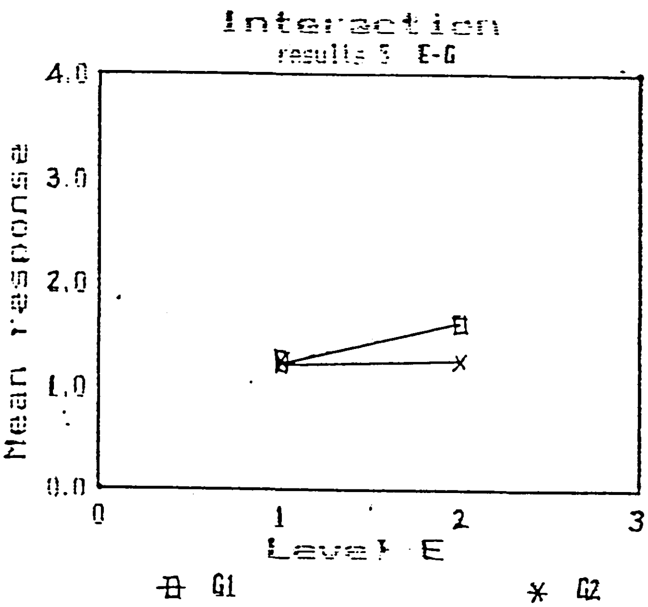

W R diff size
diff-same
B U R configuration
1-2
Speed
high-low
Front tension
high-low
Mean response
Level
0.0
1.0
2.0
3.0
4.0
0
1
2
3

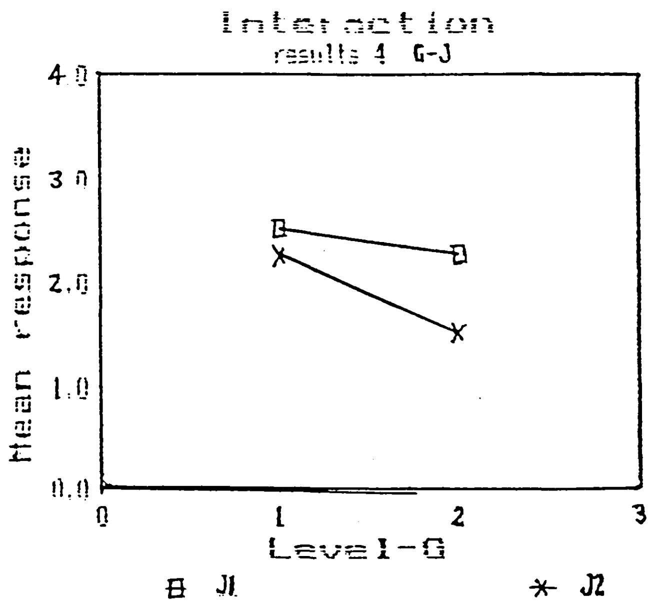
¼ buckle 0-4.

C


Interaction
results 5 A-H
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-A
H1
H2


Interaction
results 5 I-H
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-I
H1
H2


Interaction
results 5 E-G
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level E
G1
G2


Interaction
results 4 G-J
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-G
J1
J2

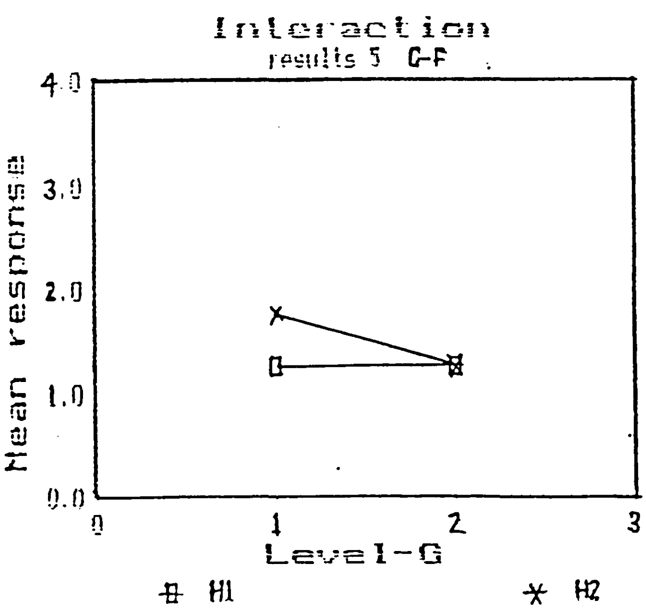
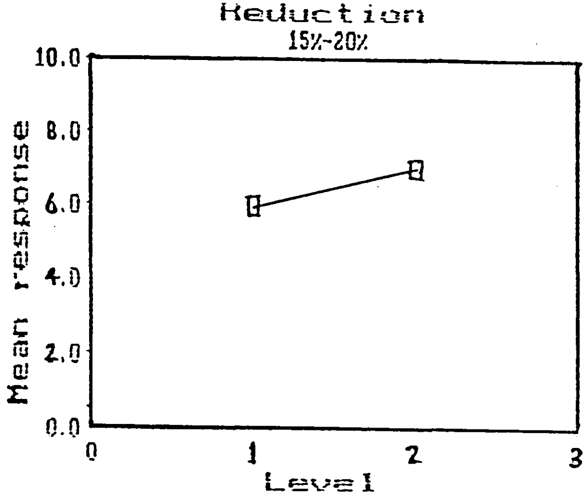
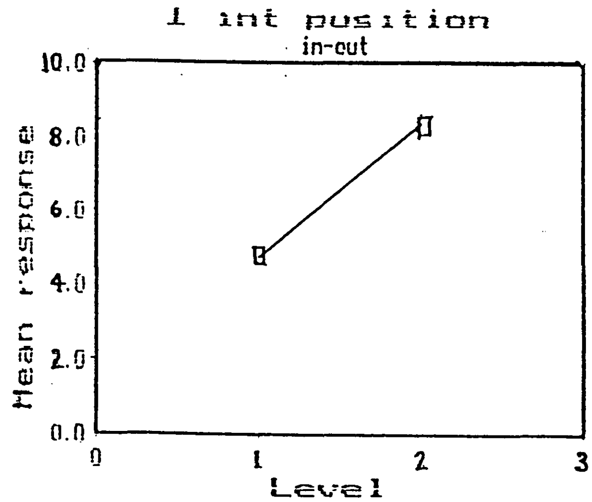
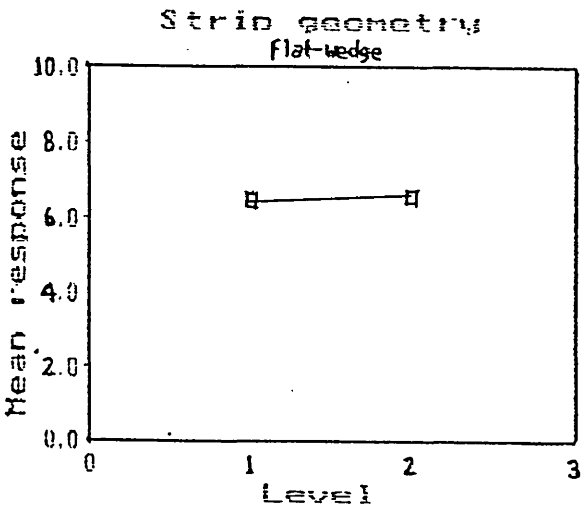
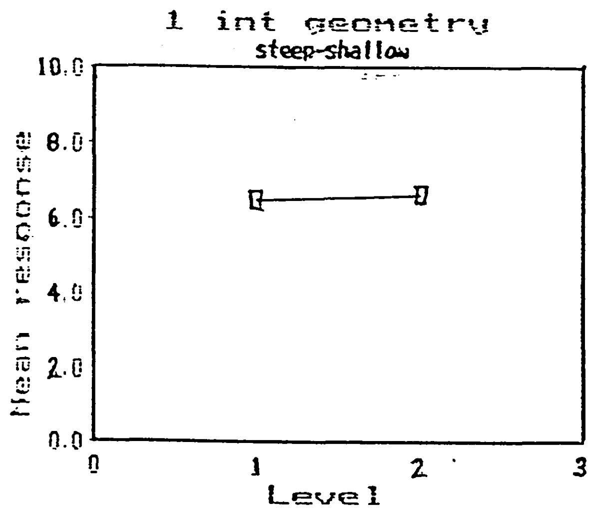

Interaction
results 5 G-F
Mean response
4.0
3.0
2.0
1.0
0.0
0
1
2
3
Level-G
H1
H2

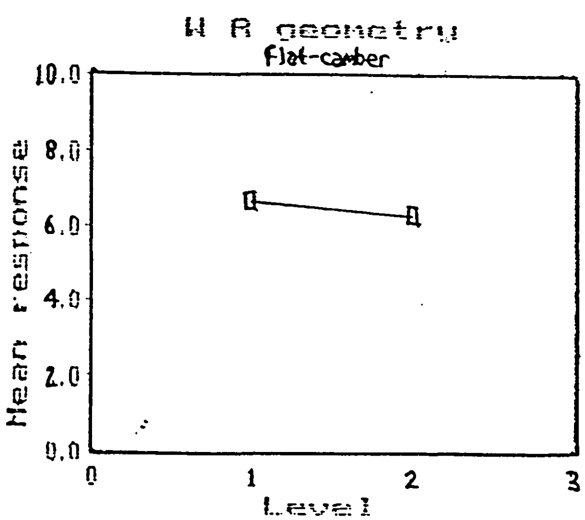
Figure 9.
Mean Response Plots and Results for the Visual Appearance Method of Recording Strip Shape Defects, from a Single Part of a Rolling Sequence.

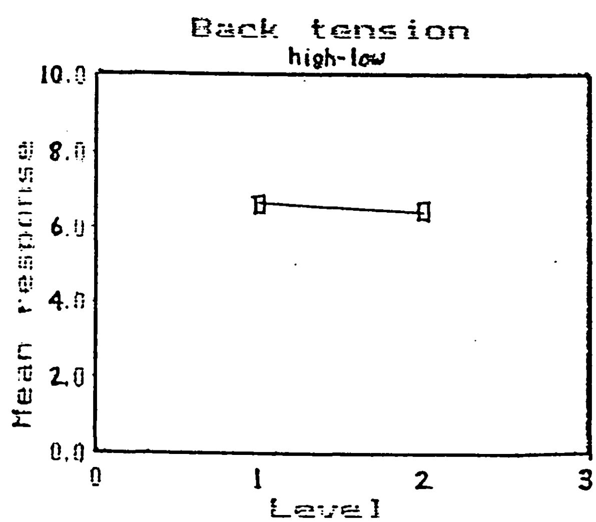






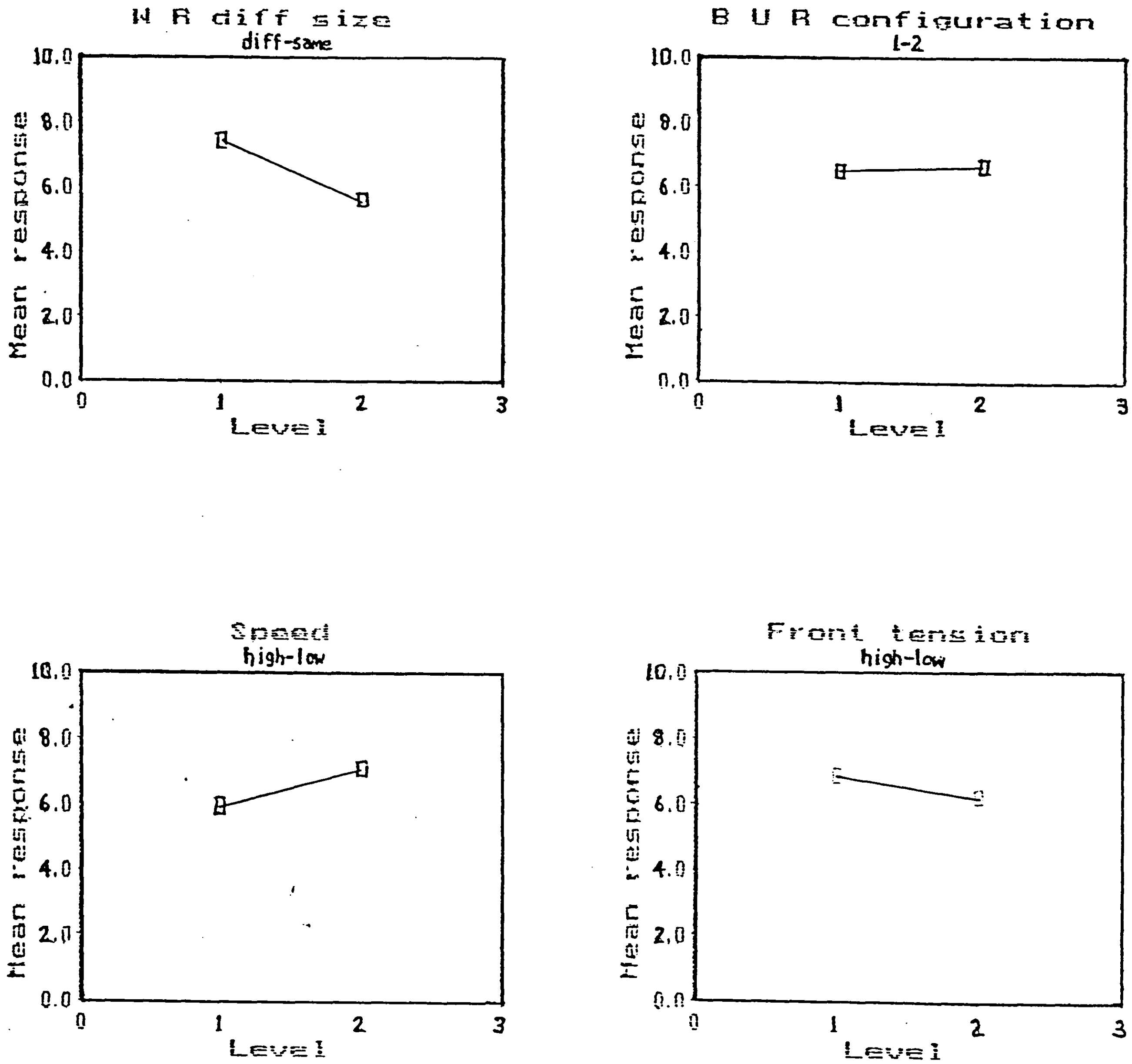




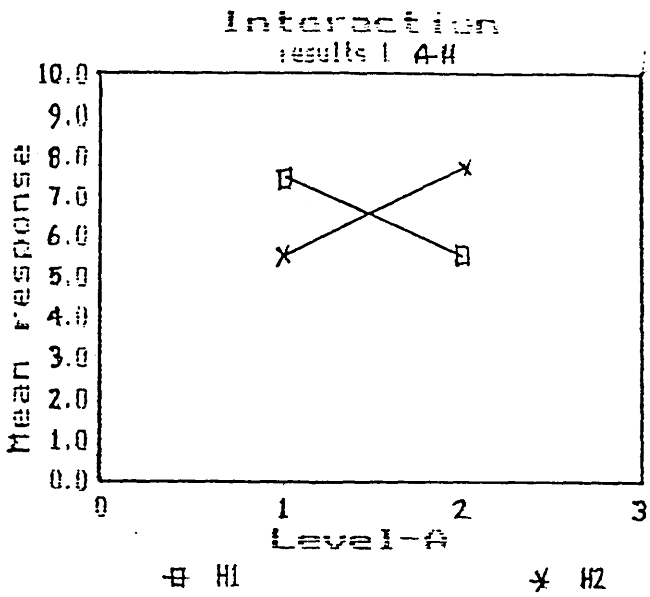


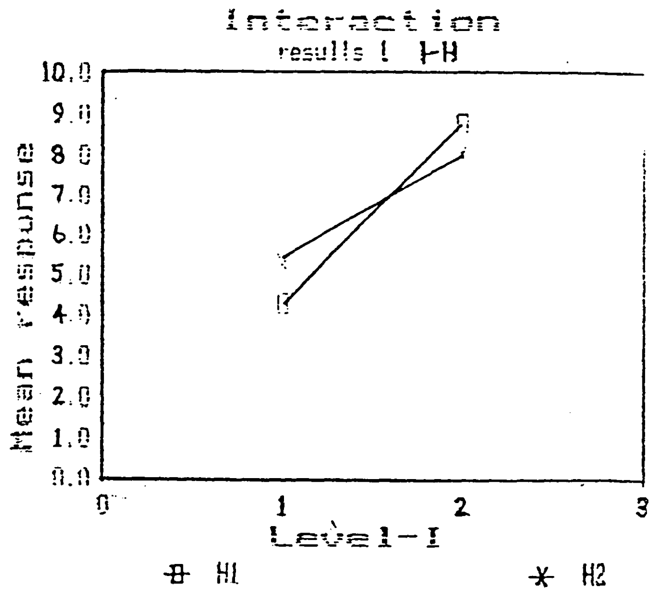
Visual Shape 1-10

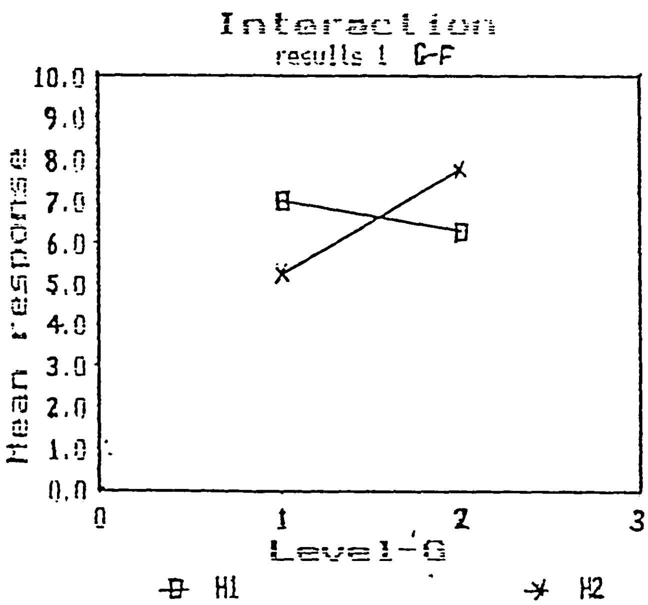
b

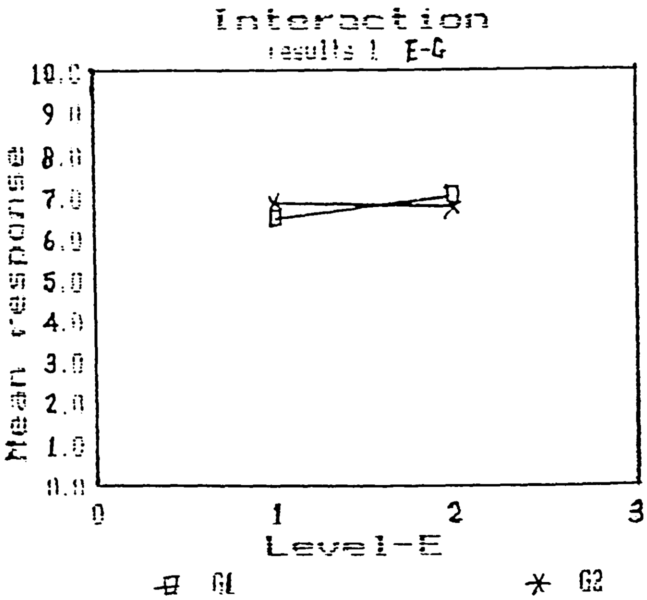


visual shape 1-10


Interaction
results 1 A-H
Mean response
Level-A
H1
H2


Interaction
results 1 I-H
Mean response
Level-I
H1
H2


Interaction
results 1 G-F
Mean response
Level-G
H1
H2


Interaction
results 1 E-G
Mean response
Level-E
G1
G2

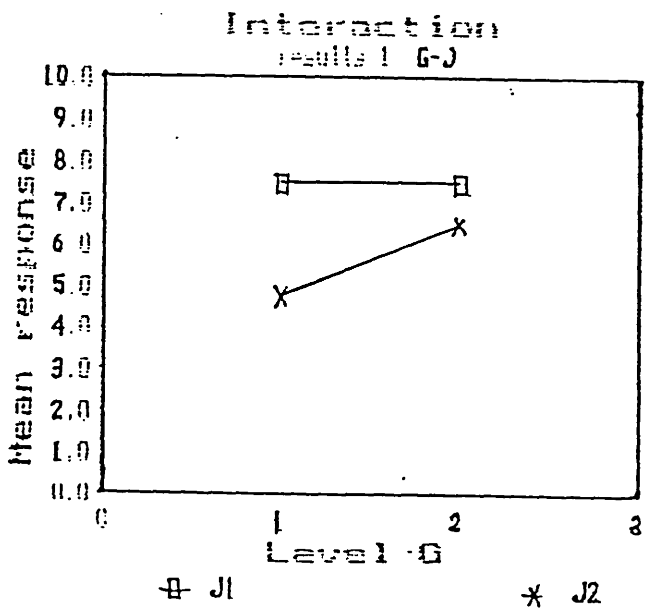
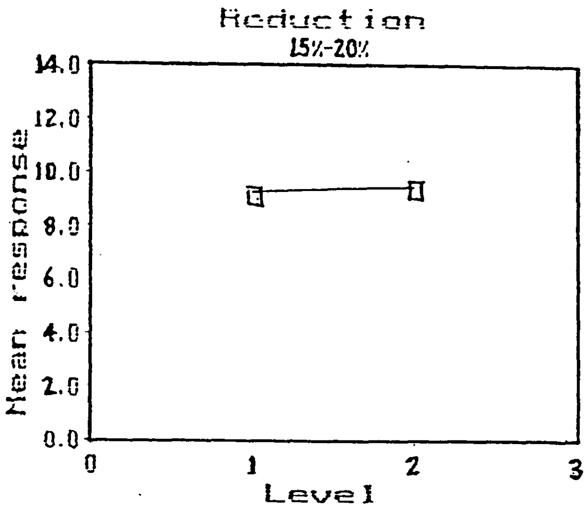
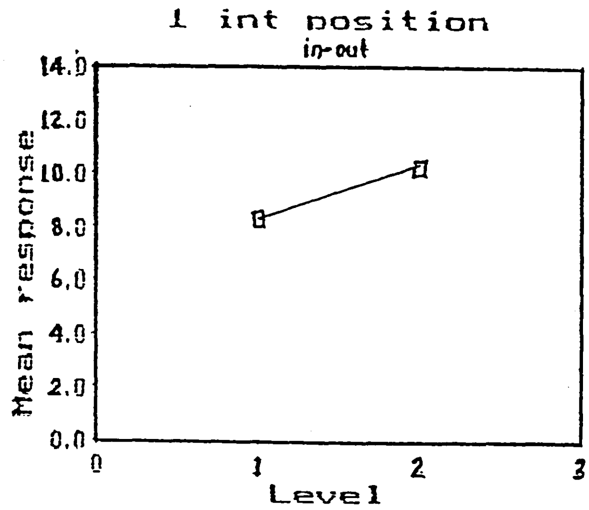
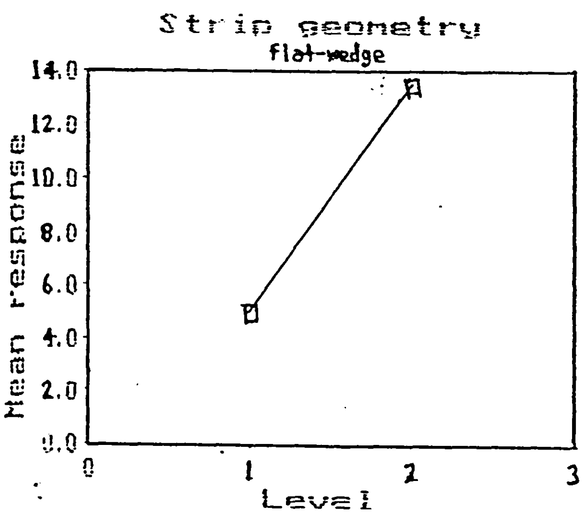
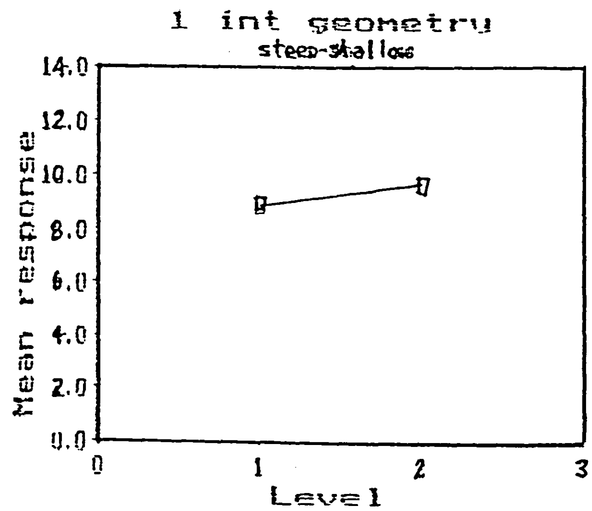

Interaction
results 1 G-J
Mean response
Level G
J1
J2

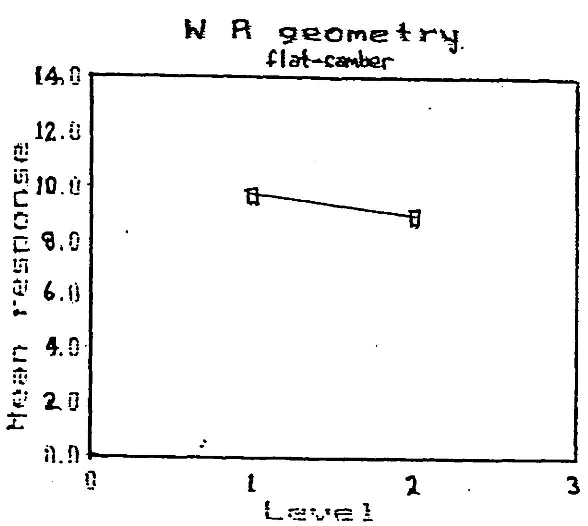
Figure 10.
Mean Response Plots and Results for the Profile Difference method of Recording Strip Shape Defects, From a single Part of a Rolling Sequence.

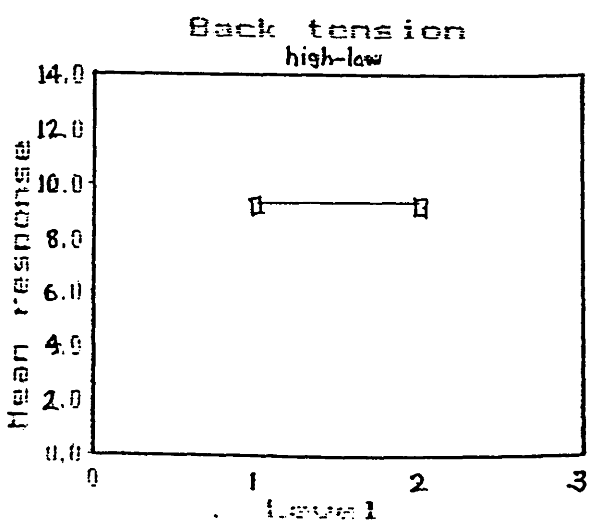

Reduction
15%-20%
Mean response
Level


1 int position
in-out
Mean response
Level


Strip geometry
flat-wedge
Mean response
Level


1 int geometry
steep-shallow
Mean response
Level

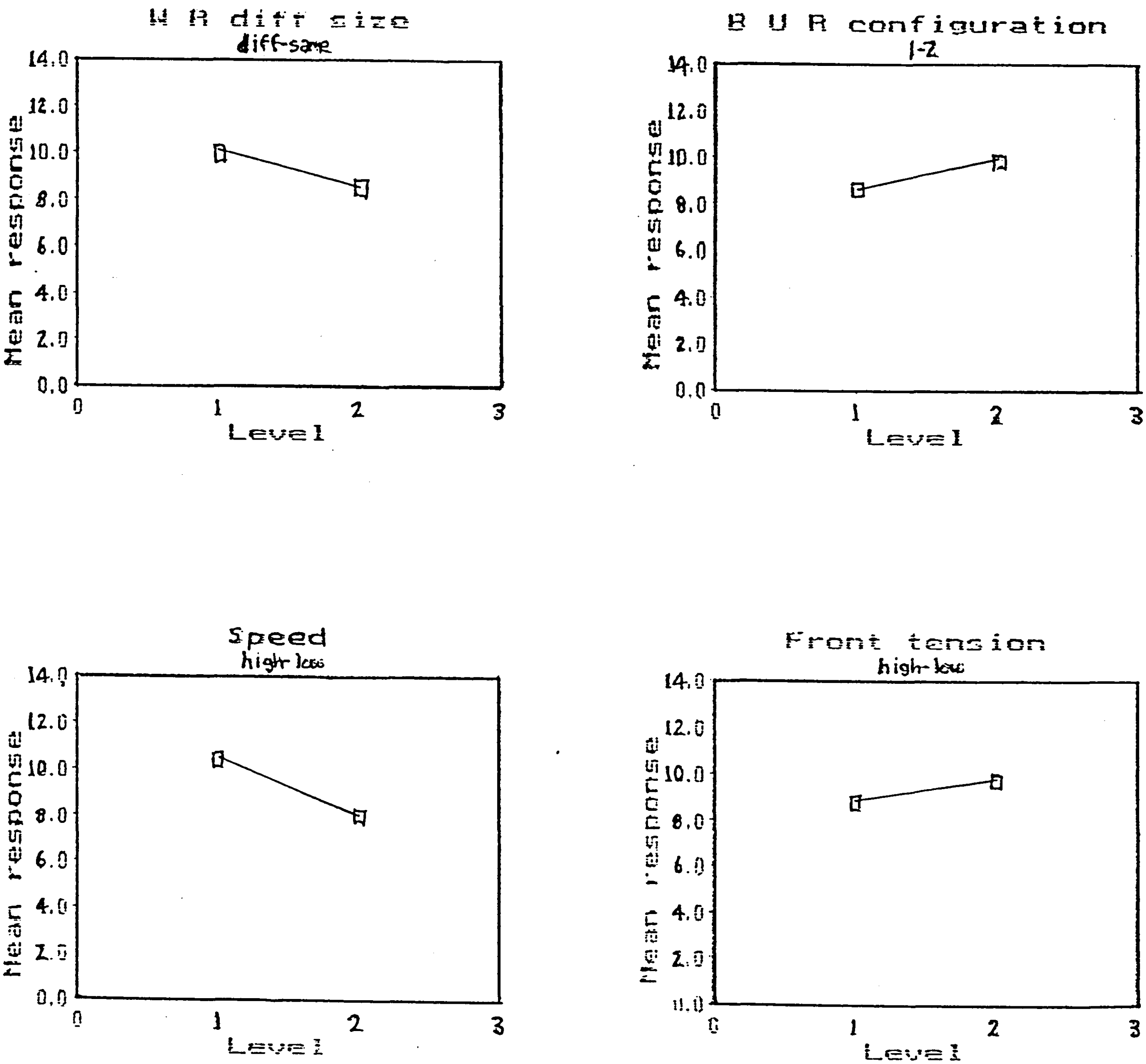

W R geometry
flat-camber
Mean response
Level


Back tension
high-low
Mean response
Level

a

Profile um

b



W R diff size
diff-same
Mean response
Level
B U R configuration
1-2
Mean response
Level
Speed
high-low
Mean response
Level
Front tension
high-low
Mean response
Level

Profile Um

Figure 11.
Mean Response Plots and Results for the Edge Wave Strip Shape Defect. Measuring the Effects of Work Roll Parameters on Strip Shape.

a

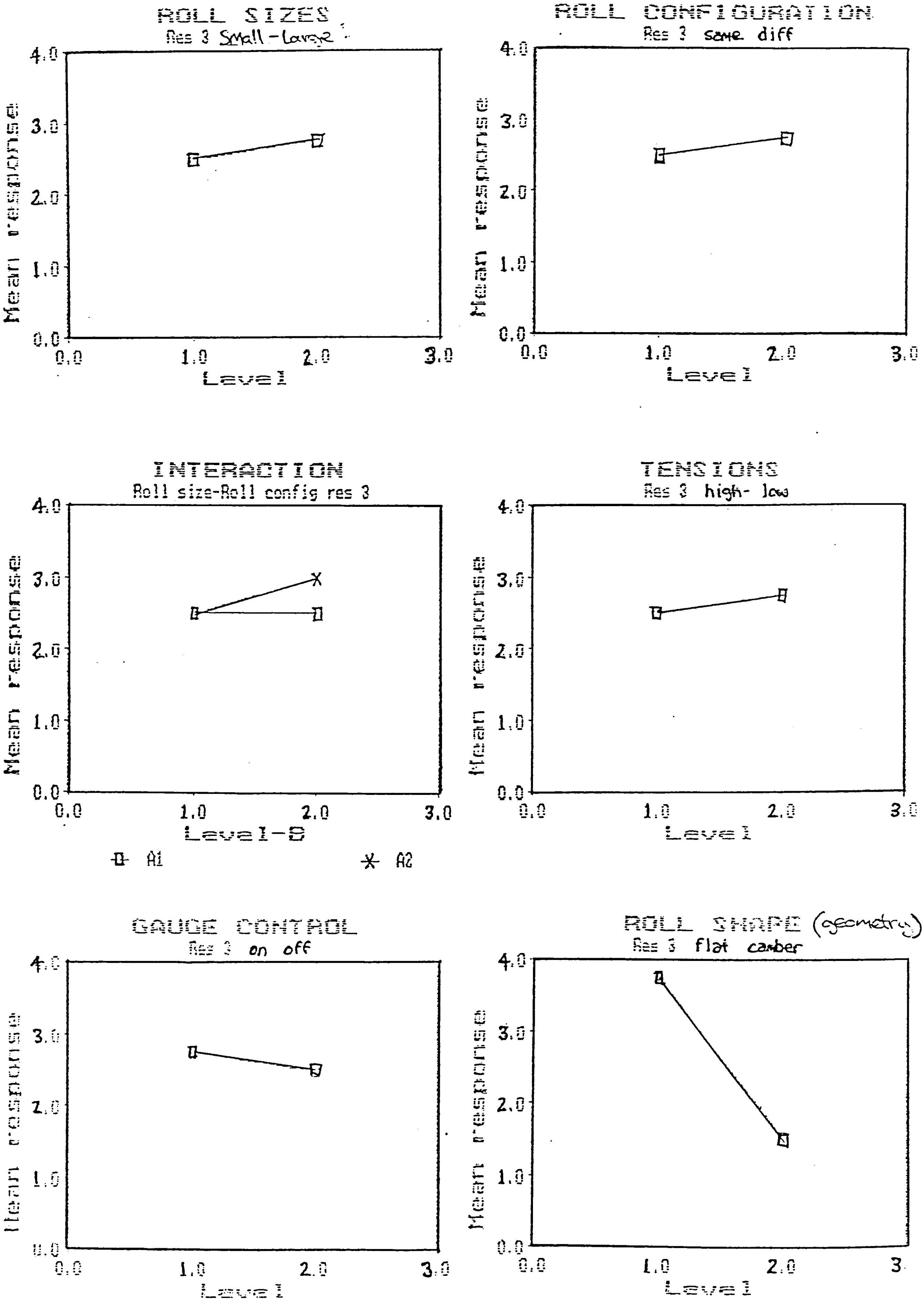
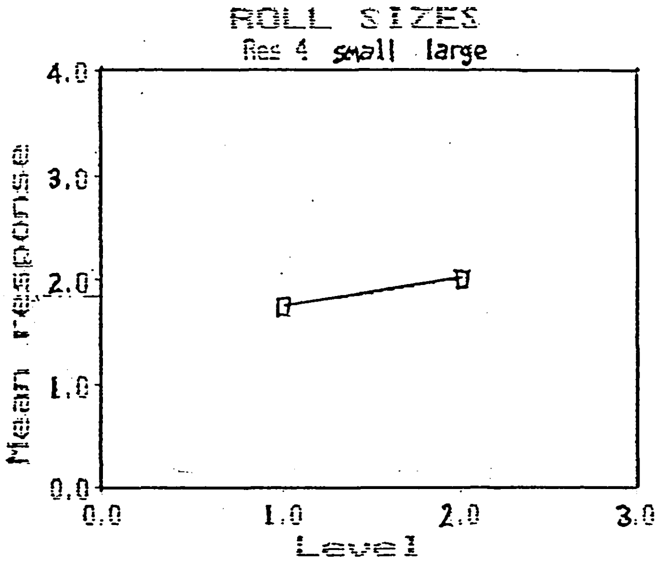
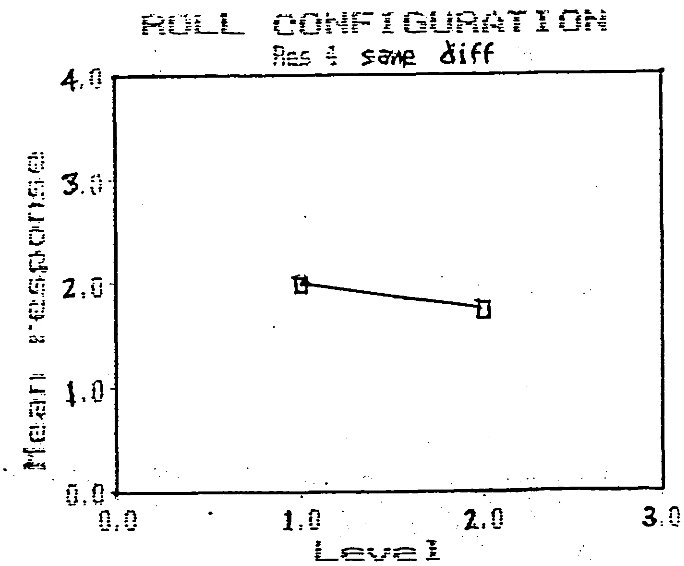
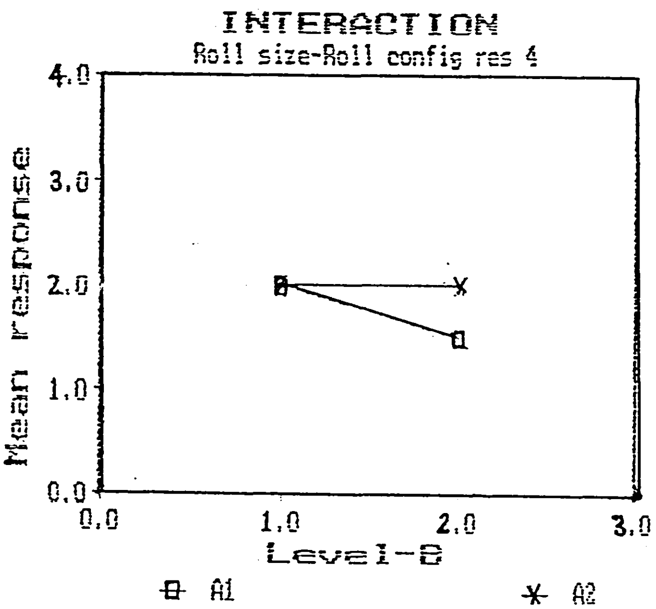

ROLL SIZES
Res 3 Small - Large
ROLL CONFIGURATION
Res 3 same diff
INTERACTION
Roll size-Roll config res 3
Level-B
A1
A2
TENSIONS
Res 3 high- low
GAUGE CONTROL
Res 3 on off
ROLL SHAPE (geometry)
Res 3 flat camber
Mean response
Level
0.0
1.0
2.0
3.0
4.0

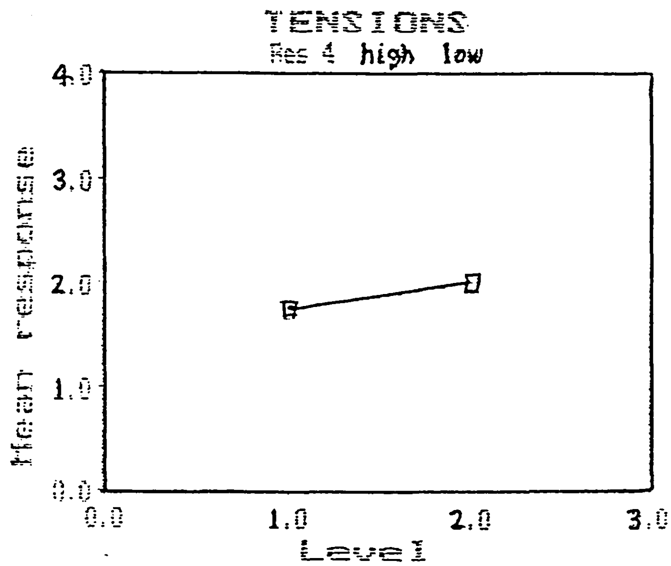
Figure 12.

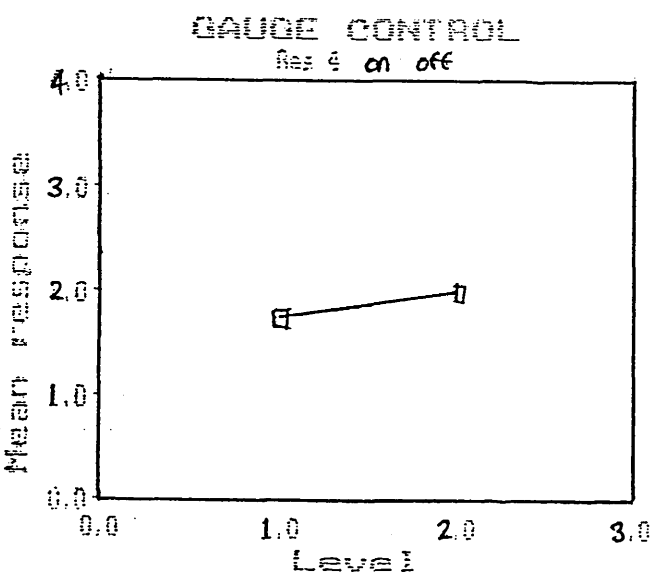
Mean Response Plots and Results for the Full Centre Strip Shape Defect. Measuring the effects of Work Roll Parameters on Strip Shape.


ROLL SIZES
Res 4 small large
Mean response
Level


ROLL CONFIGURATION
Res 4 same diff
Mean response
Level


INTERACTION
Roll size-Roll config res 4
Mean response
Level-B
A1
A2


TENSIONS
Res 4 high low
Mean response
Level


GAUGE CONTROL
Res 4 on off
Mean response
Level

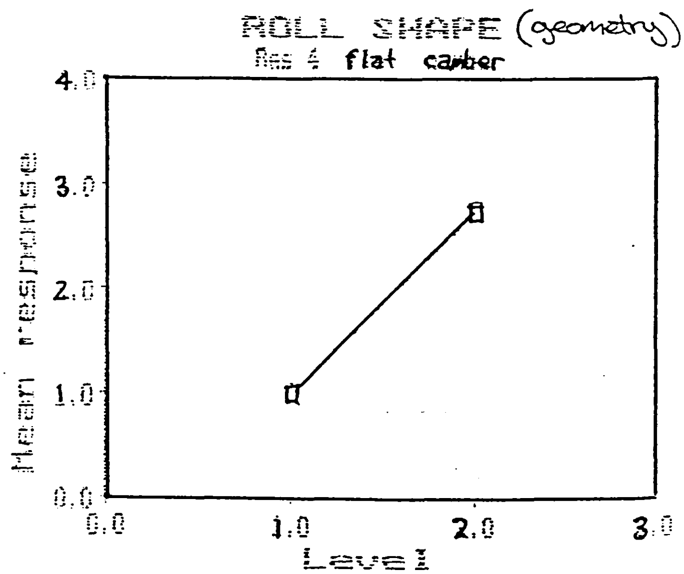
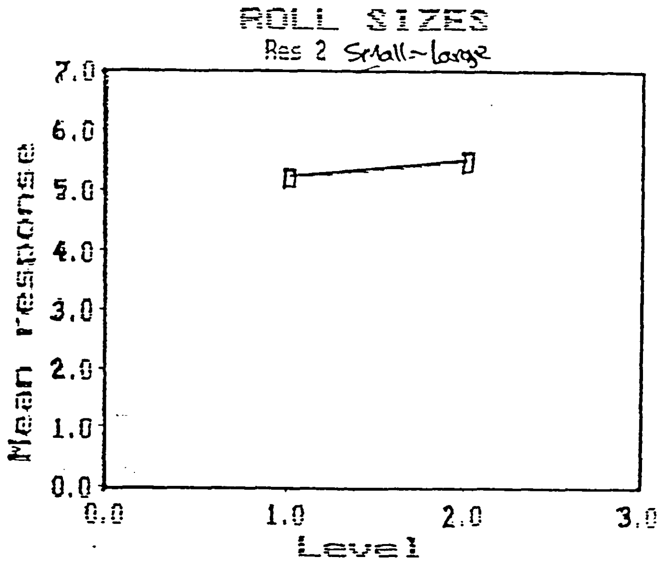
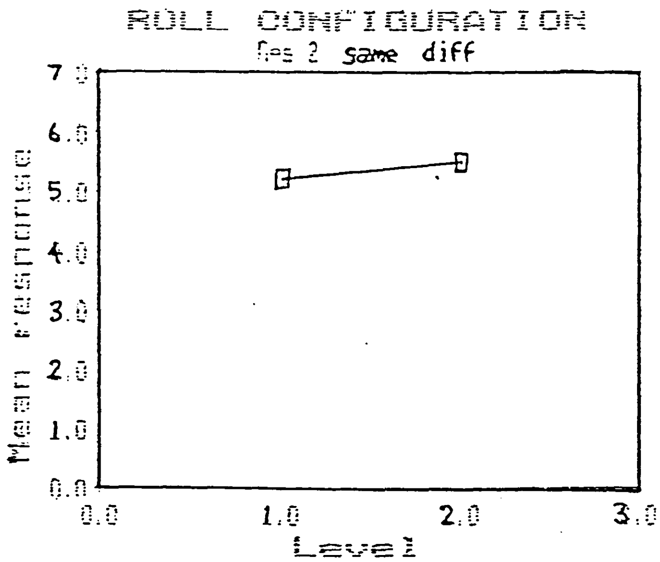
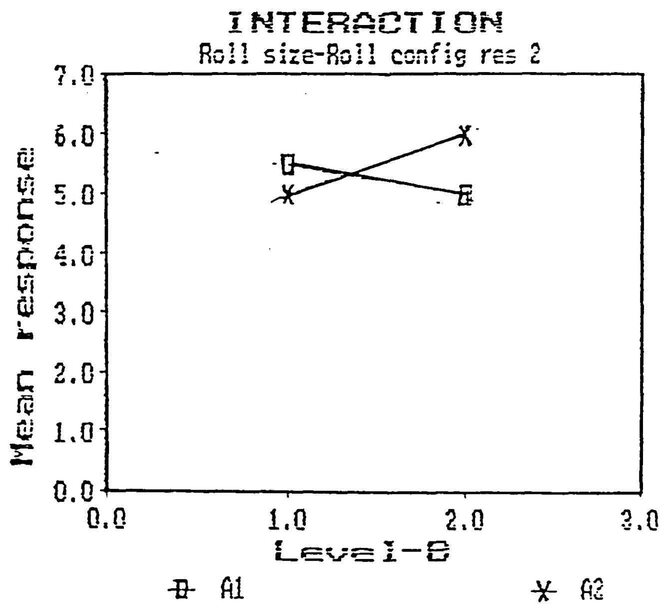
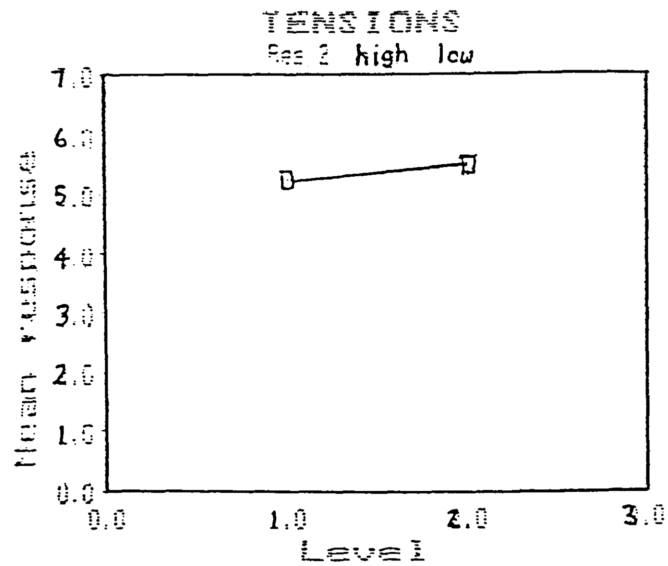

ROLL SHAPE (geometry)
Res 4 flat camber
Mean response
Level

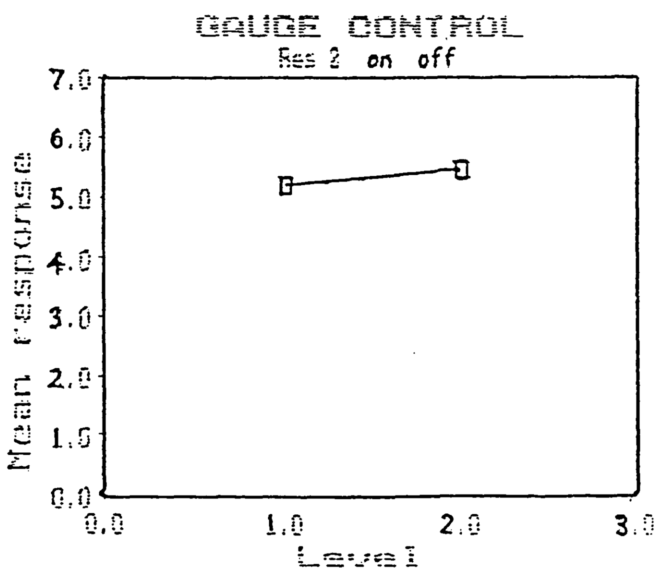
Figure 13.
Mean Response Plots and Results for the Visual Appearance Method of Recording Strip Shape Defects. Measuring the Effects of Work Roll Parameters on Strip Shape.


ROLL SIZES
Res 2 Small~large
Mean response
Level
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0


ROLL CONFIGURATION
Res 2 same diff
Mean response
Level
0.0
1.0
2.0
3.0


INTERACTION
Roll size-Roll config res 2
Mean response
Level-B
A1
A2


TENSIONS
Res 2 high low
Mean response
Level


GAUGE CONTROL
Res 2 on off
Mean response
Level

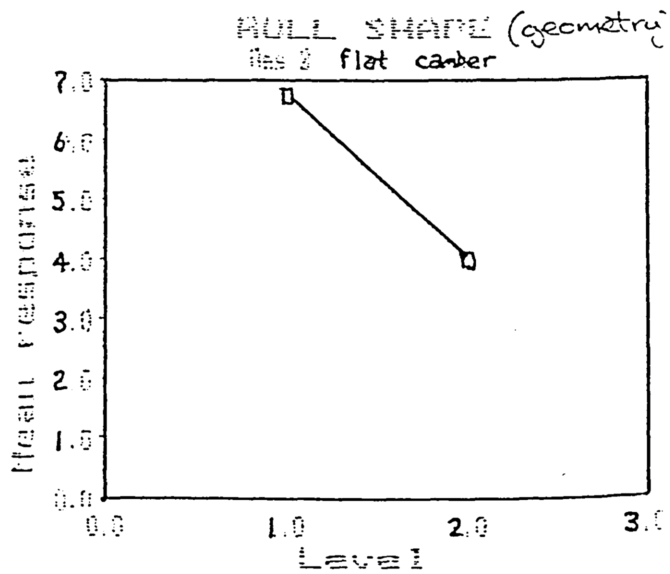
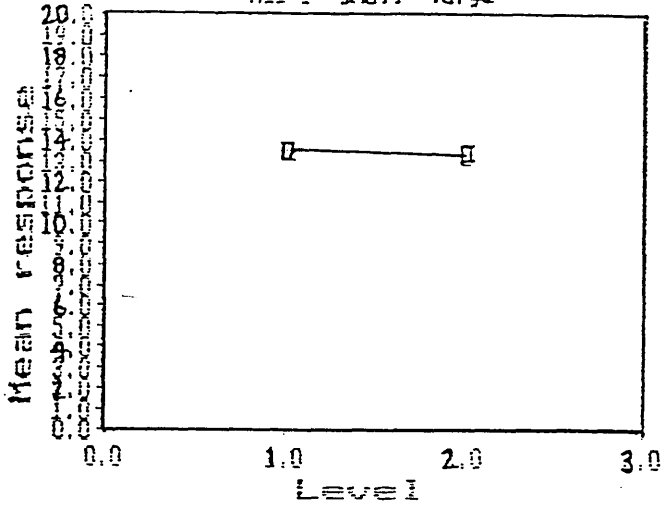

ROLL SHAPE (geometry
Res 2 flat camber
Mean response
Level

Figure 14.

Mean Response Plots and Results for the Profile Difference Method of Recording Strip Shape Defects. Measuring the Effects of Work Roll Parameters on Strip Shape.

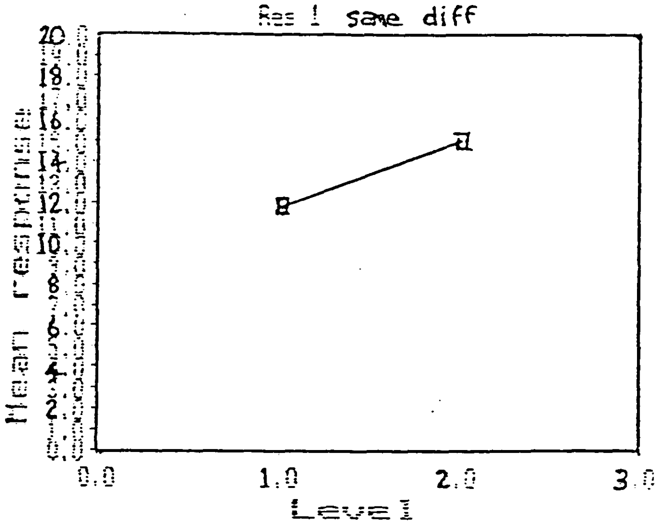
ROLL SIZES

Res 1 small large



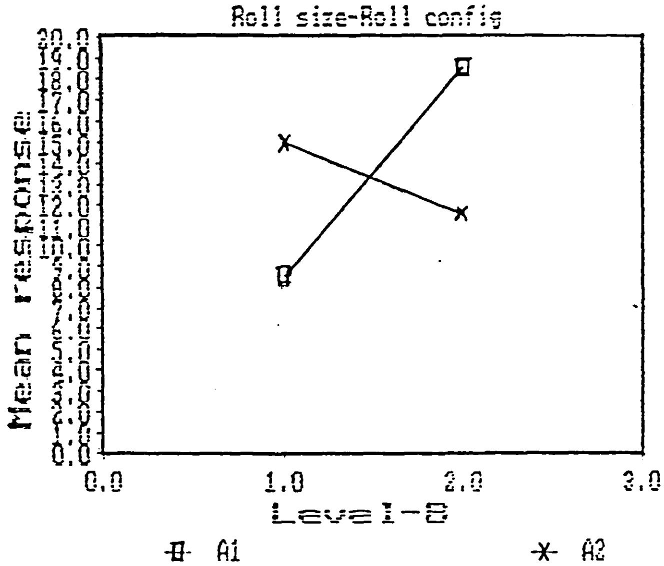
ROLL CONFIGURATION

Res 1 same diff



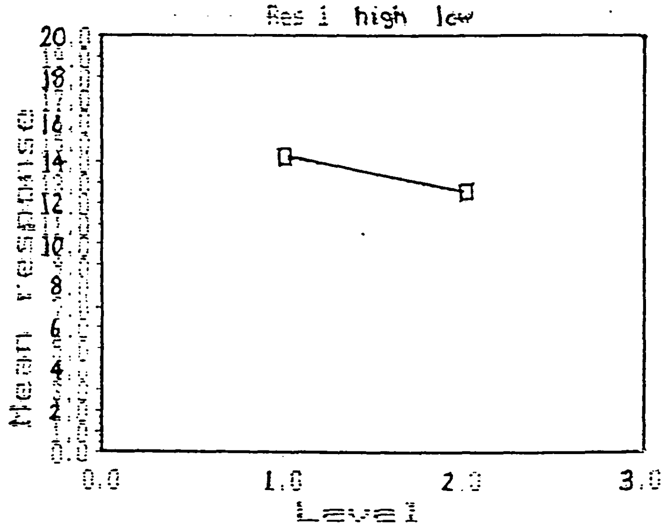
INTERACTION

Roll size-Roll config



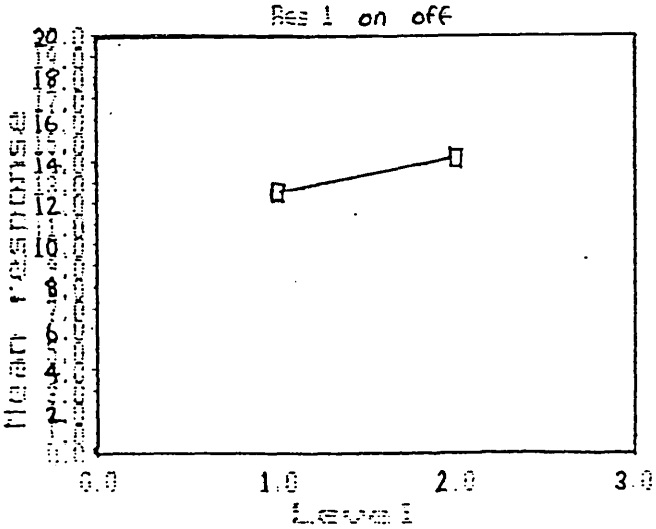
TENSIONS

Res 1 high low



GAUGE CONTROL

Res 1 on off



ROLL SHAPE (geometry)

Res 1 flat camber

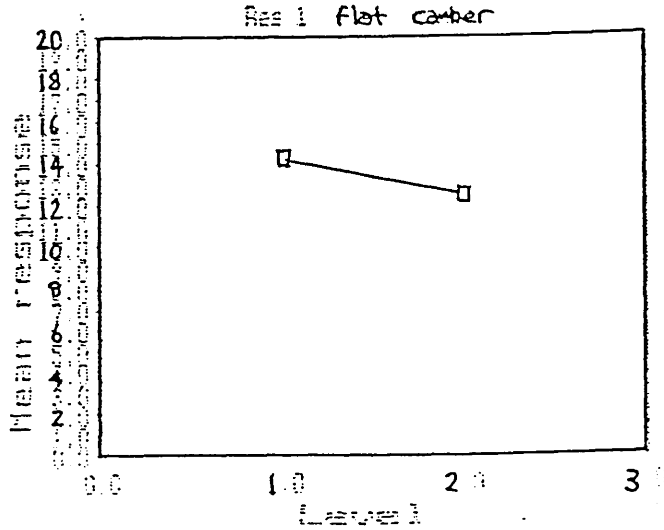
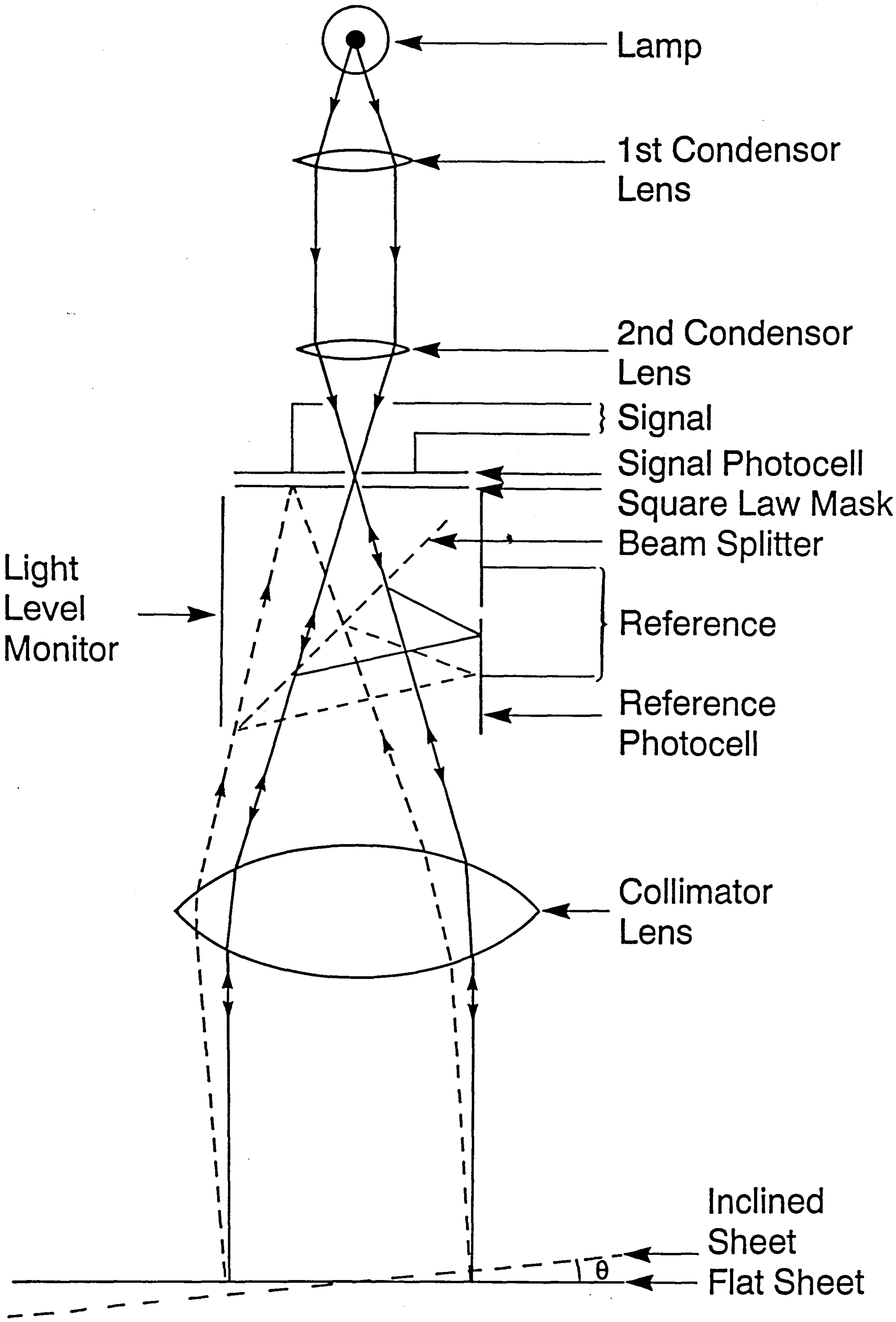


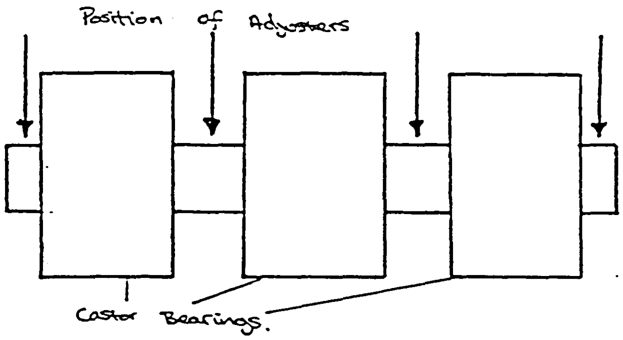
Figure 15.
Technique Used for Measuring Strip Shape.
Off-Line Optical Shapemeter.

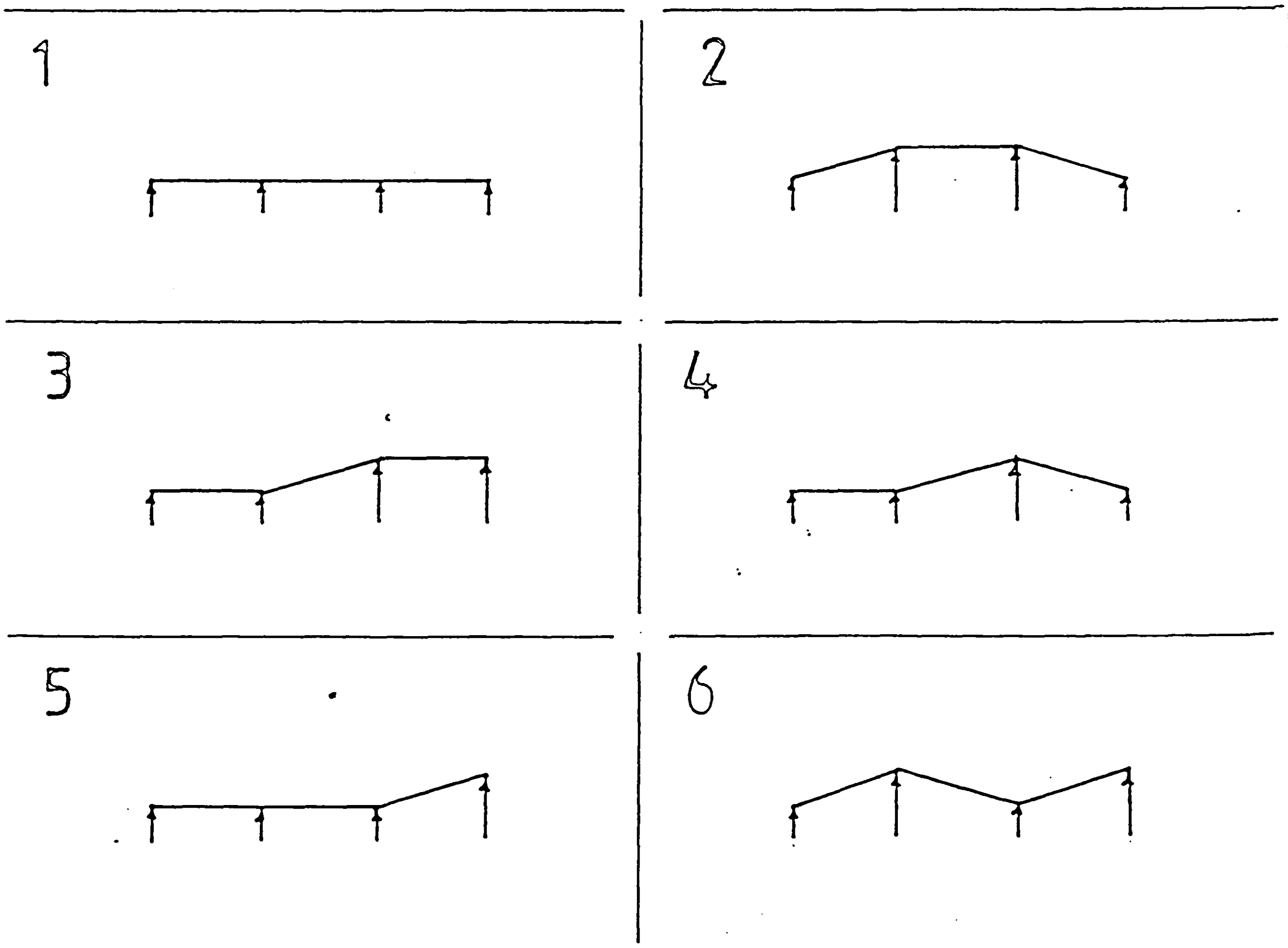


Developed by Fulmer Materials
formerly B.N.F Metals Technology

Figure 16.
Positions of Saddle Adjusters for Tests on Rolling Short Lengths of Strip.

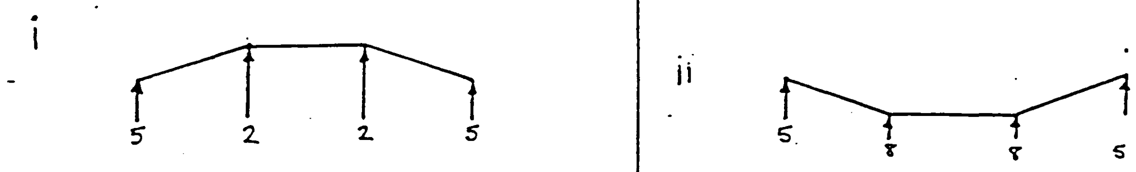
Positions of Saddle Adjusters for Rolling Short Strip Lengths.





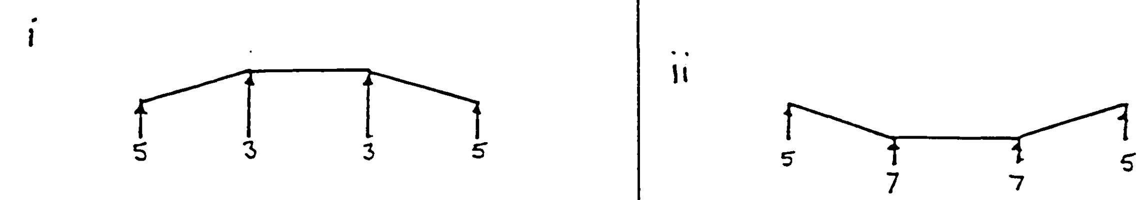
a

Positions of Saddle Adjusters for Rolling the Finishing Pass



Positions of Saddle Adjusters for Rolling a complete Pass Sequence

b



C

Positions of Saddle Adjusters for Work Roll Strain Measurements

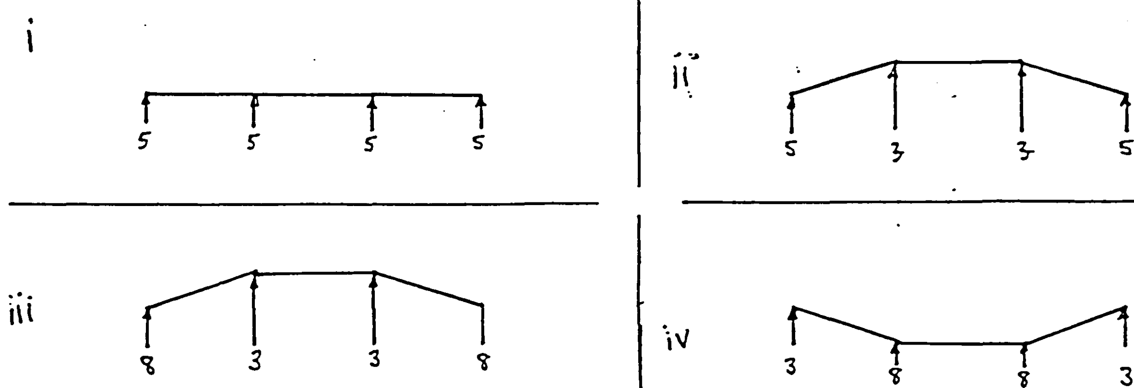
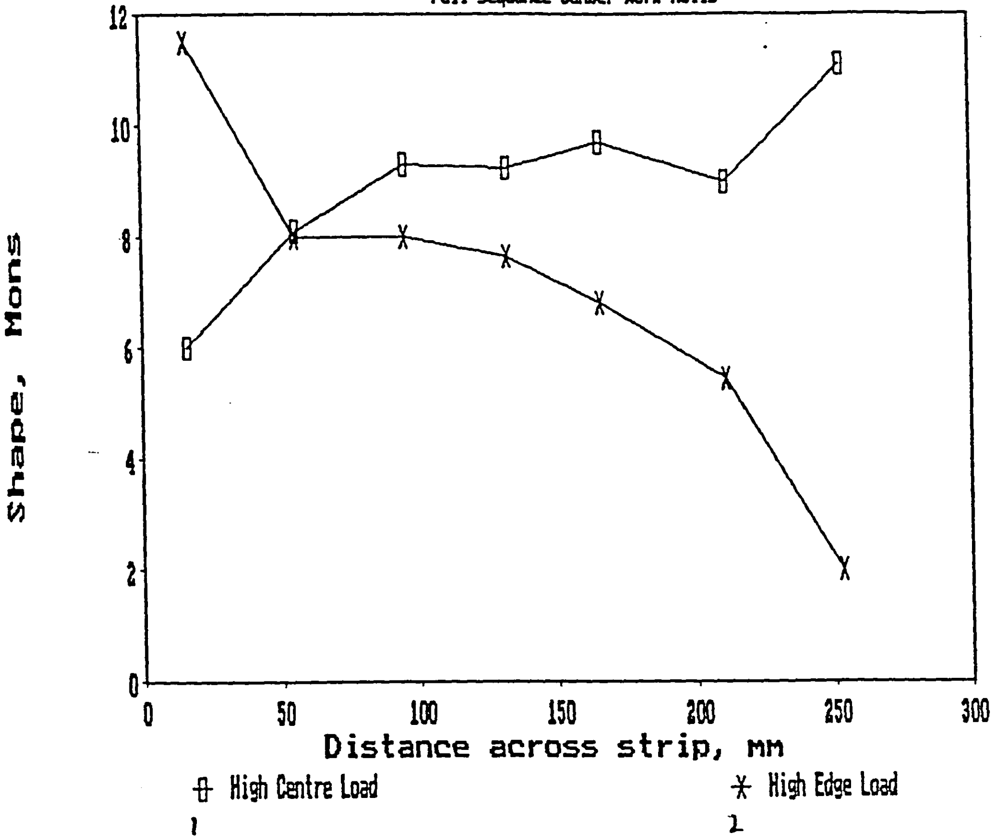


Figure 18.
Strip Shape Samples Showing the Effects of Altering the Saddles and the Work Roll Configuration Through a Rolling Sequence.

Effect of Saddle Position on Shape

Full sequence-Camber Work Rolls



Effect of Saddle Position on Shape

Full Sequence-Flat Work Rolls

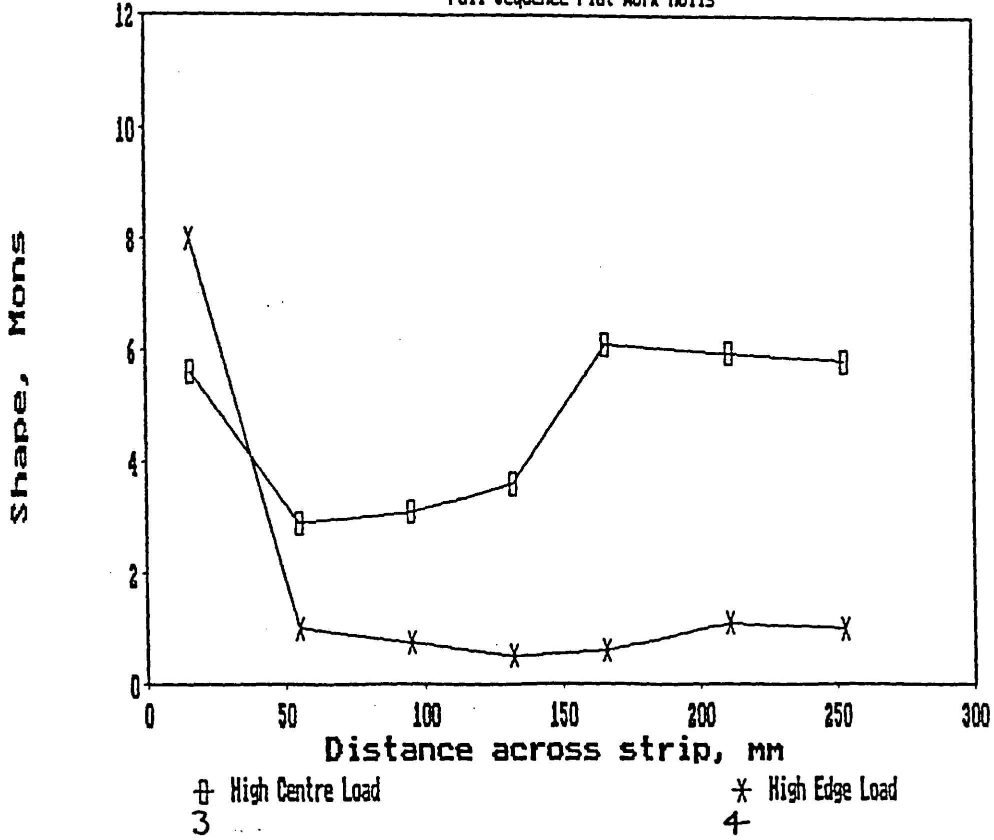
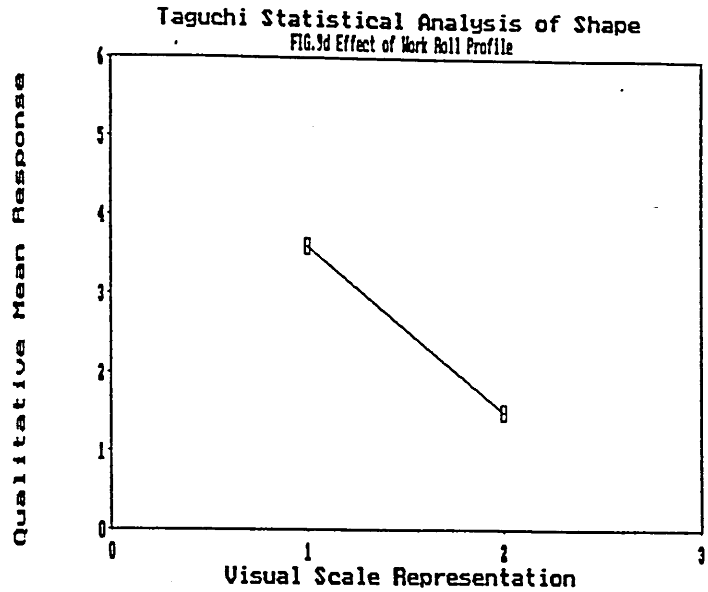


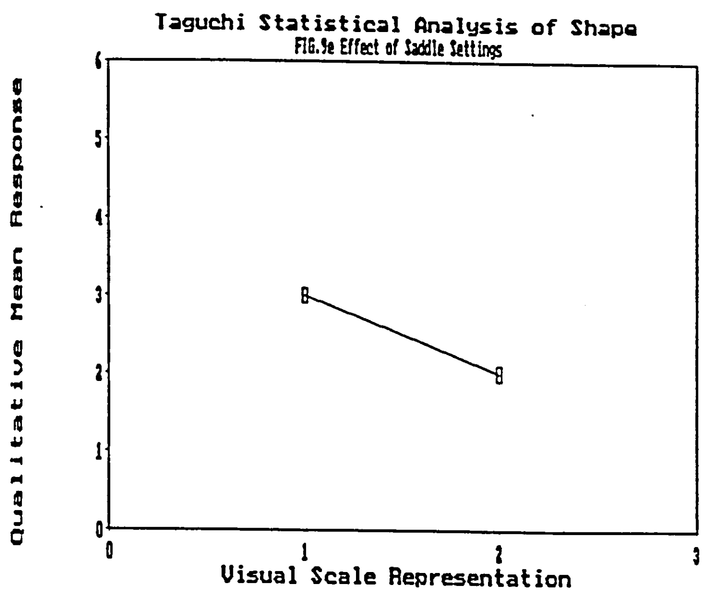
Figure 19.

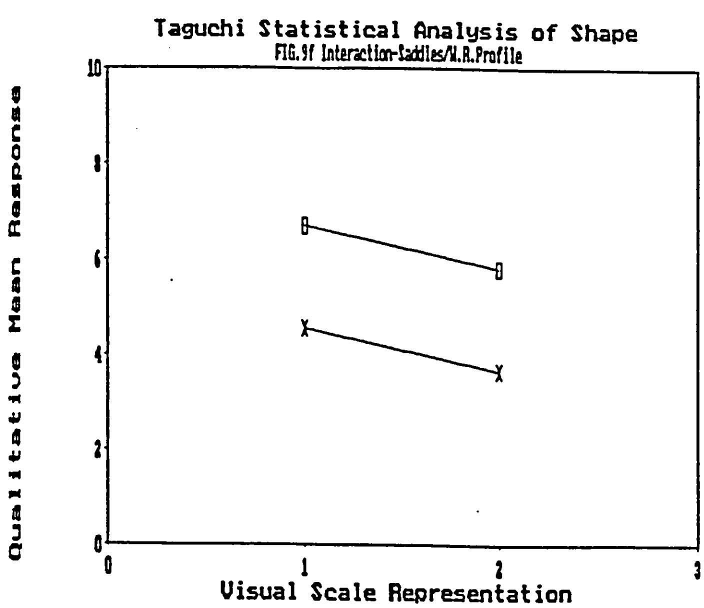
Mean Response Plots and Results of the Effects of Work Roll Profile and Saddle Settings on Strip Shape. Tests Carried out Through a Complete Rolling Sequence.

a) Visual Scale Method of Recording Results.
b) Averaging Shape Measurements Method of Recording Results.

a


Taguchi Statistical Analysis of Shape
FIG.9d Effect of Work Roll Profile
Qualitative Mean Response
Visual Scale Representation
0
1
2
3
4
5
6

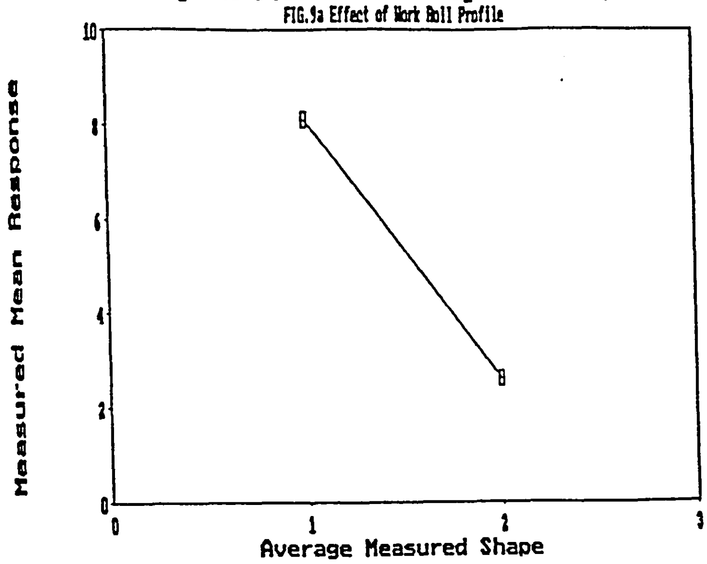

Taguchi Statistical Analysis of Shape
FIG.9e Effect of Saddle Settings
Qualitative Mean Response
Visual Scale Representation
0
1
2
3
4
5
6


Taguchi Statistical Analysis of Shape
FIG.9f Interaction-Saddles/W.R.Profile
Qualitative Mean Response
Visual Scale Representation
0
1
2
3
4
6
8
10

b

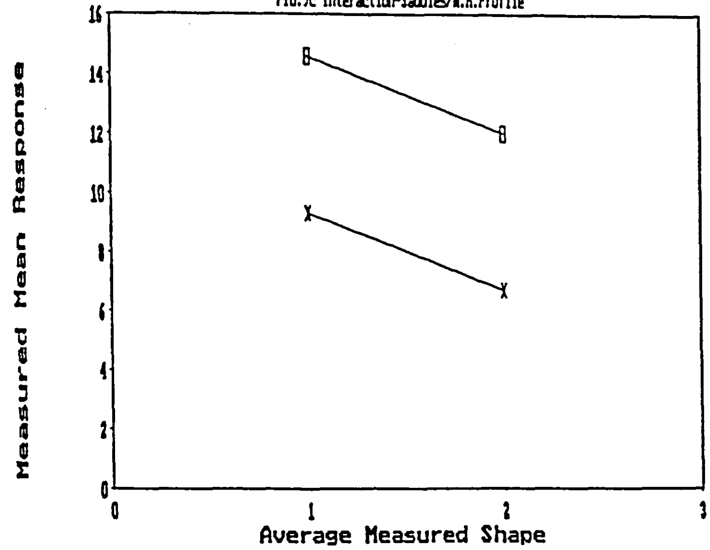
Taguchi Statistical Analysis of Shape

FIG.9a Effect of Work Roll Profile



Taguchi Statistical Analysis of Shape

FIG.9c Interaction-Saddles/W.R.Profile



Taguchi Statistical Analysis of Shape

FIG.9b Effect of Saddle Settings

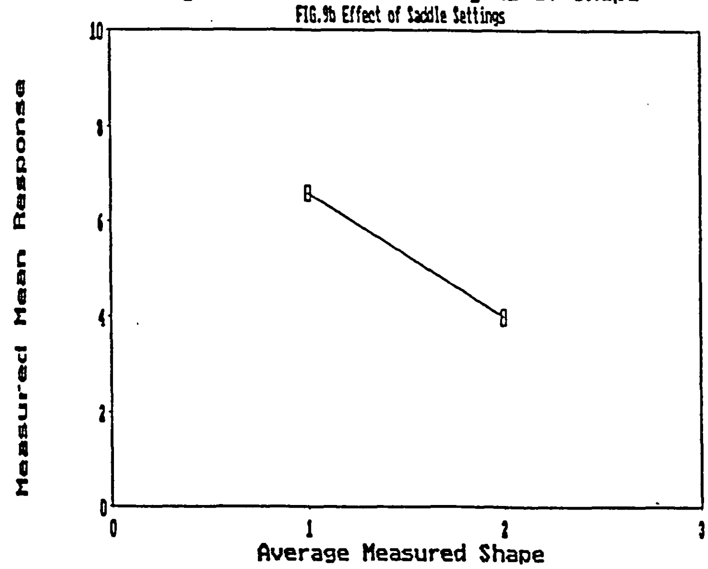
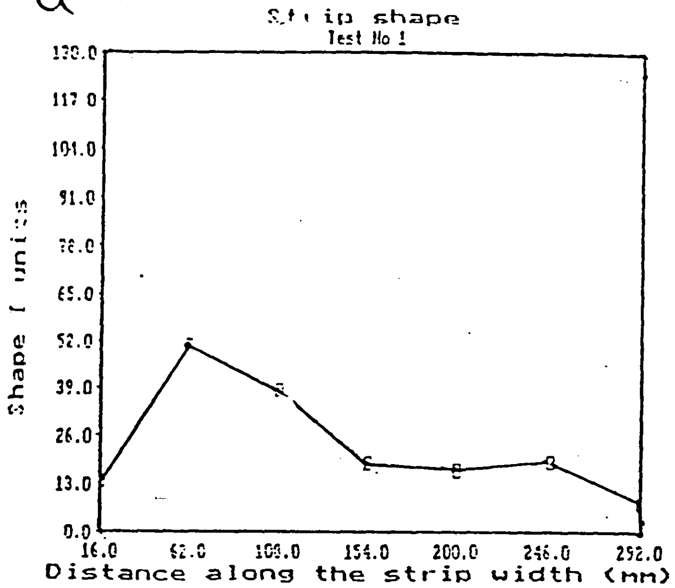
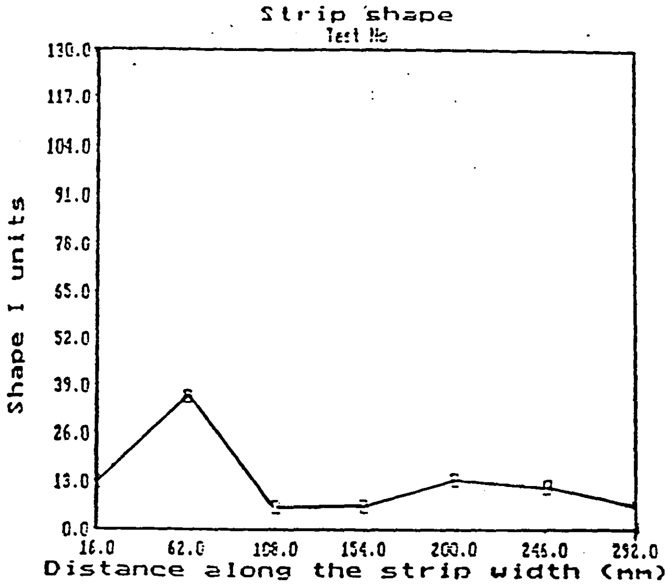


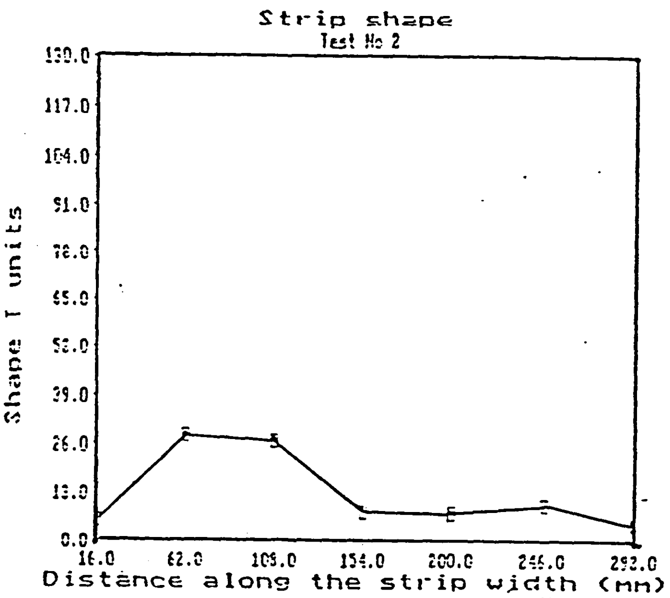
Figure 20.
Strip Shape Plots Showing the Effects of Rolling Parameters on Strip Shape Throughout a Complete Rolling Sequence.

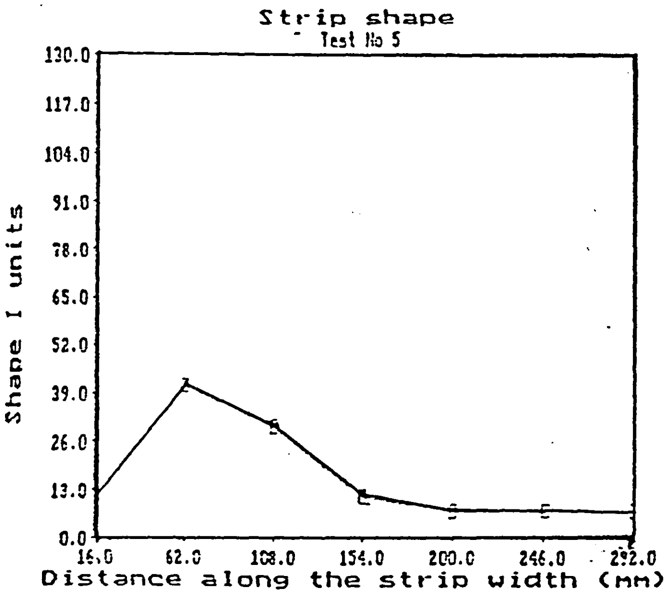
Material Type; 316 Austenitic Stainless Steel
Reduction; 75/ From 1.22mm to 0.305mm
Strip Width; 312mm

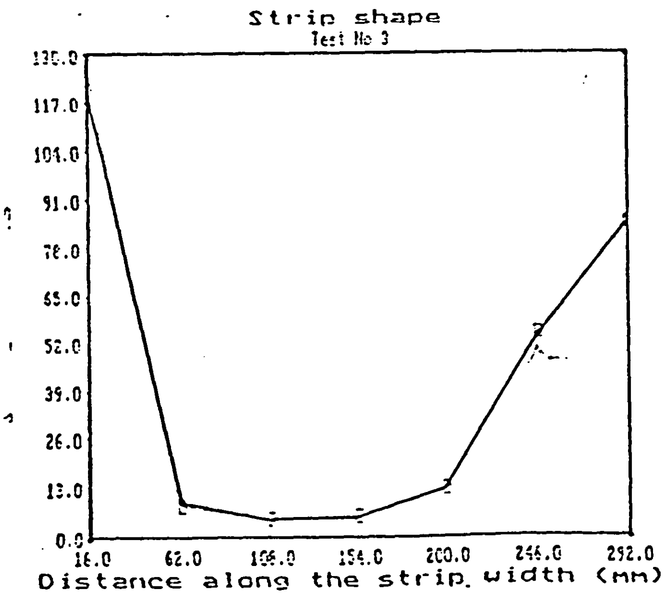
a

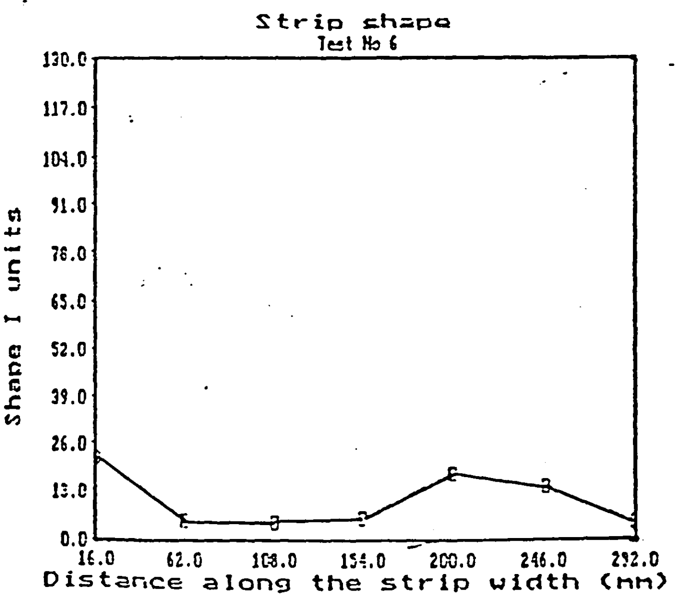

Strip shape
Test No 1
Shape I units
130.0 117.0 104.0 91.0 78.0 65.0 52.0 39.0 26.0 13.0 0.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0
Distance along the strip width (mm)


Strip shape
Test No
Shape I units
130.0 117.0 104.0 91.0 78.0 65.0 52.0 39.0 26.0 13.0 0.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0
Distance along the strip width (mm)

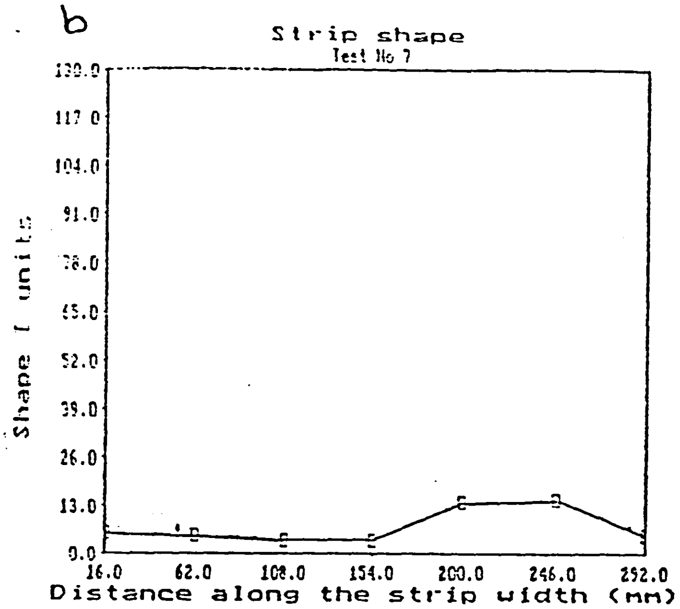

Strip shape
Test No 2
Shape I units
130.0 117.0 104.0 91.0 78.0 65.0 52.0 39.0 26.0 13.0 0.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0
Distance along the strip width (mm)

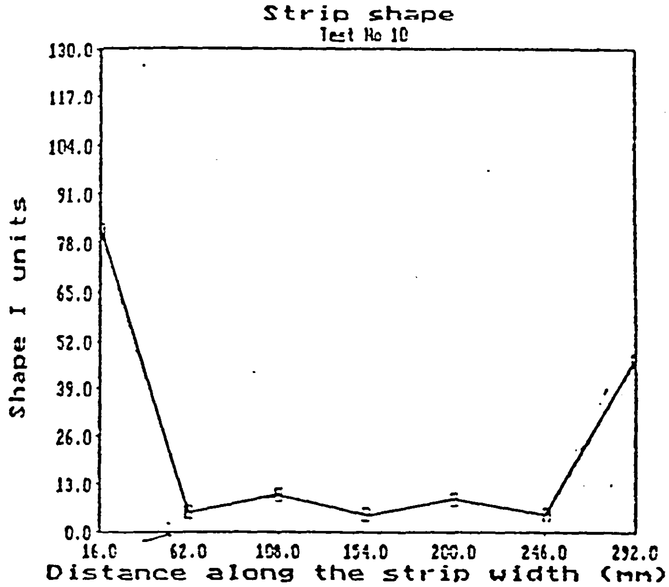

Strip shape
Test No 5
Shape I units
130.0 117.0 104.0 91.0 78.0 65.0 52.0 39.0 26.0 13.0 0.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0
Distance along the strip width (mm)

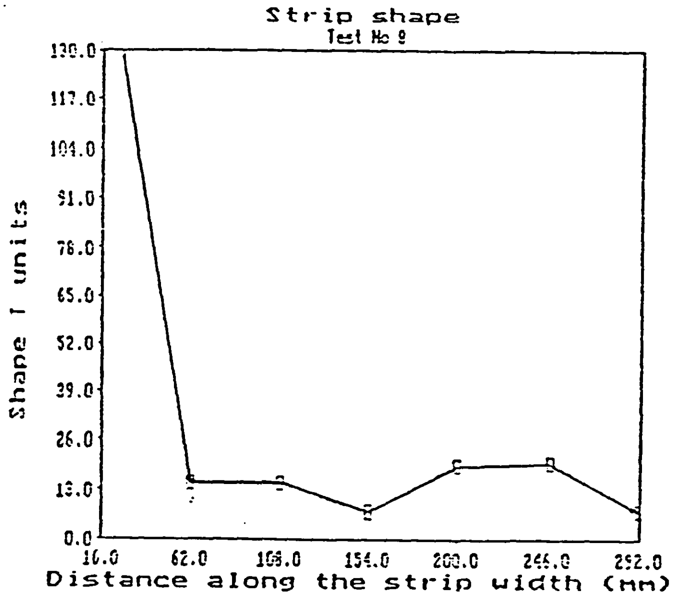

Strip shape
Test No 3
130.0 117.0 104.0 91.0 78.0 65.0 52.0 39.0 26.0 13.0 0.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0
Distance along the strip width (mm)

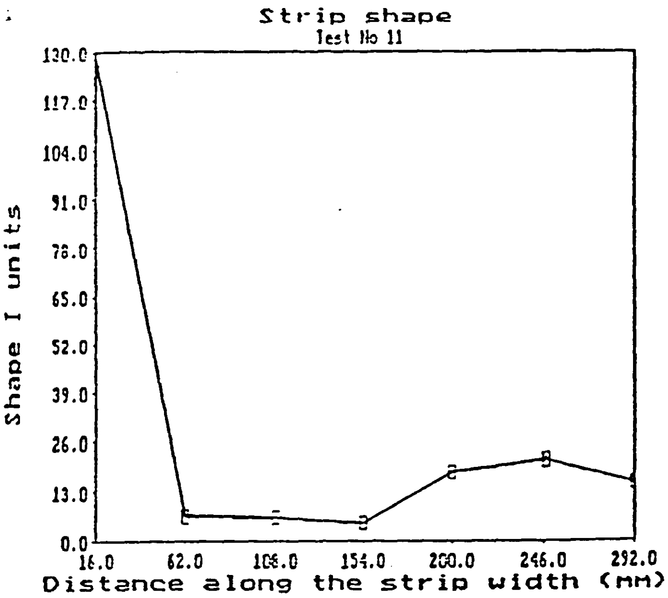

Strip shape
Test No 6
Shape I units
130.0 117.0 104.0 91.0 78.0 65.0 52.0 39.0 26.0 13.0 0.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0
Distance along the strip width (mm)

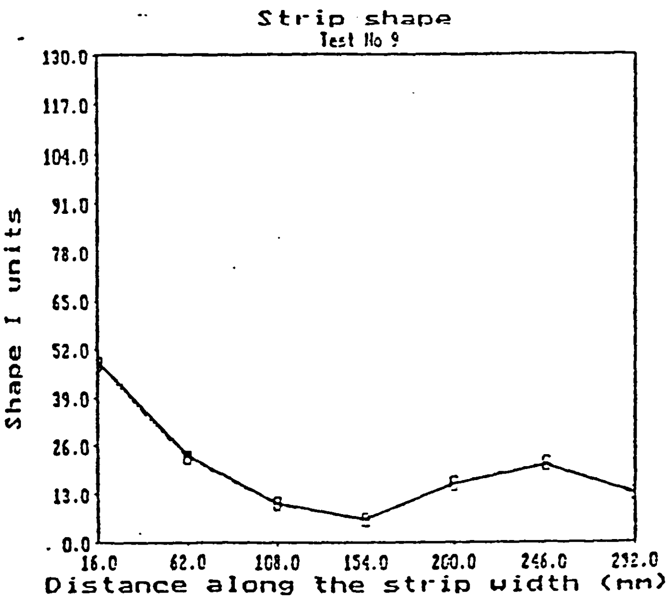
b

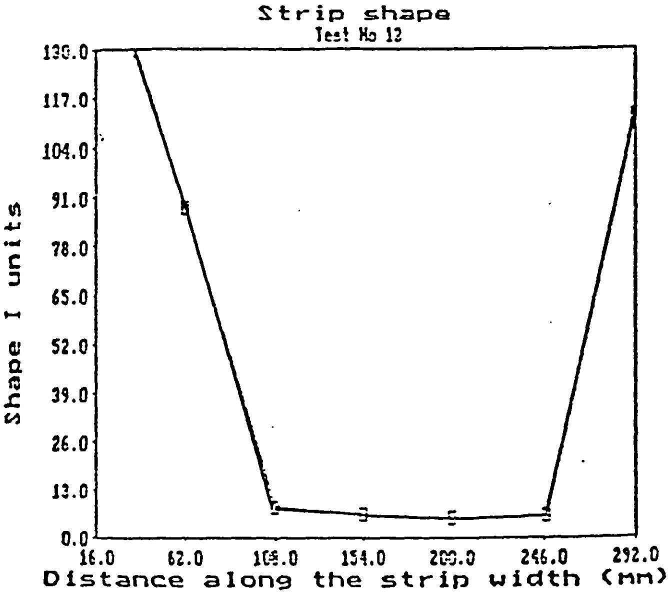

Strip shape
Test No 7
Shape I units
Distance along the strip width (mm)
0.0 13.0 26.0 39.0 52.0 65.0 78.0 91.0 104.0 117.0 130.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0


Strip shape
Test No 10
Shape I units
Distance along the strip width (mm)
0.0 13.0 26.0 39.0 52.0 65.0 78.0 91.0 104.0 117.0 130.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0

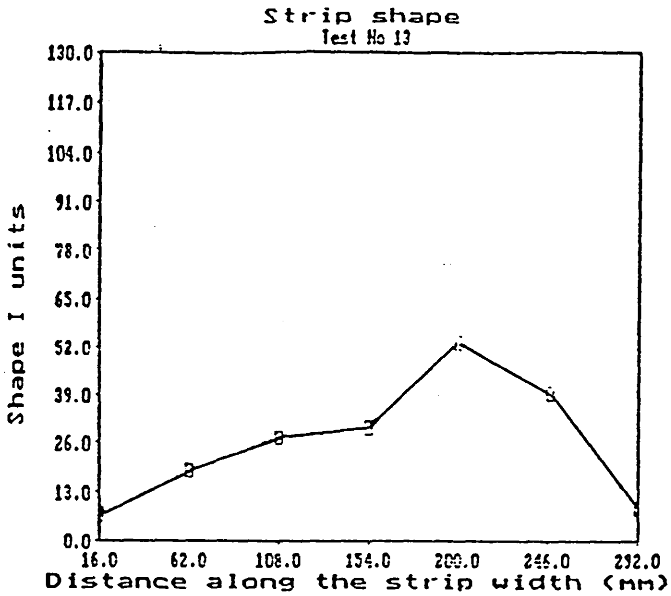

Strip shape
Test No 8
Shape I units
Distance along the strip width (mm)
0.0 13.0 26.0 39.0 52.0 65.0 78.0 91.0 104.0 117.0 130.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0


Strip shape
Test No 11
Shape I units
Distance along the strip width (mm)
0.0 13.0 26.0 39.0 52.0 65.0 78.0 91.0 104.0 117.0 130.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0

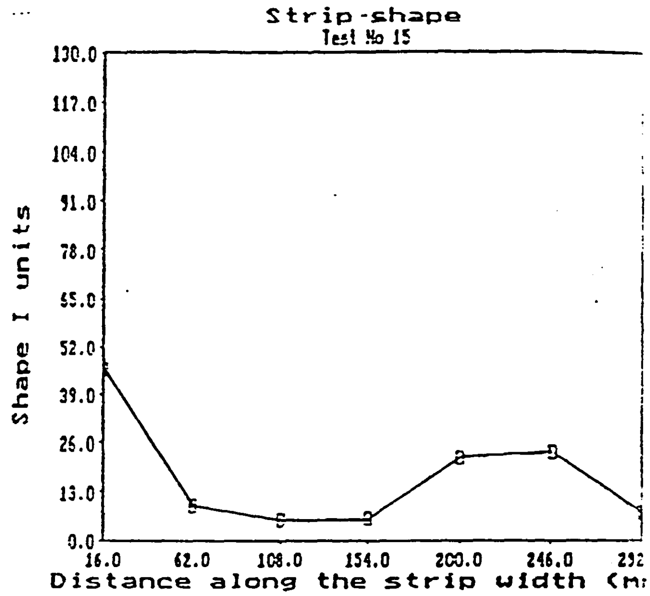

Strip shape
Test No 9
Shape I units
Distance along the strip width (mm)
0.0 13.0 26.0 39.0 52.0 65.0 78.0 91.0 104.0 117.0 130.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0


Strip shape
Test No 12
Shape I units
Distance along the strip width (mm)
0.0 13.0 26.0 39.0 52.0 65.0 78.0 91.0 104.0 117.0 130.0
16.0 62.0 108.0 154.0 200.0 246.0 292.0

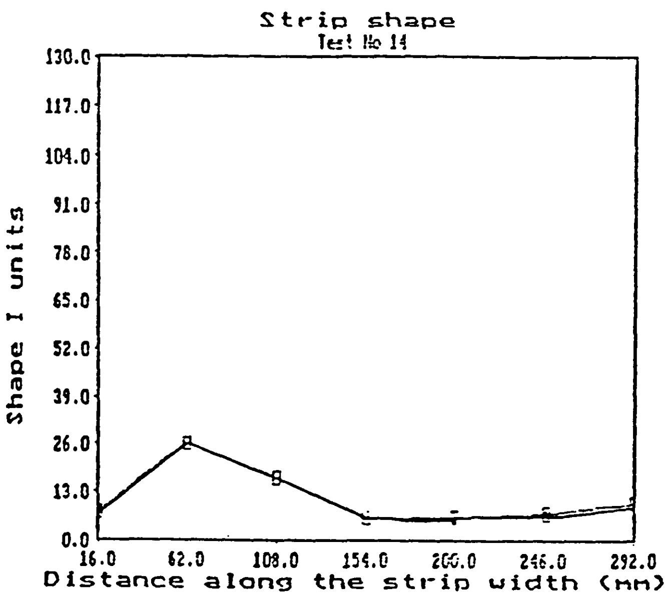
c



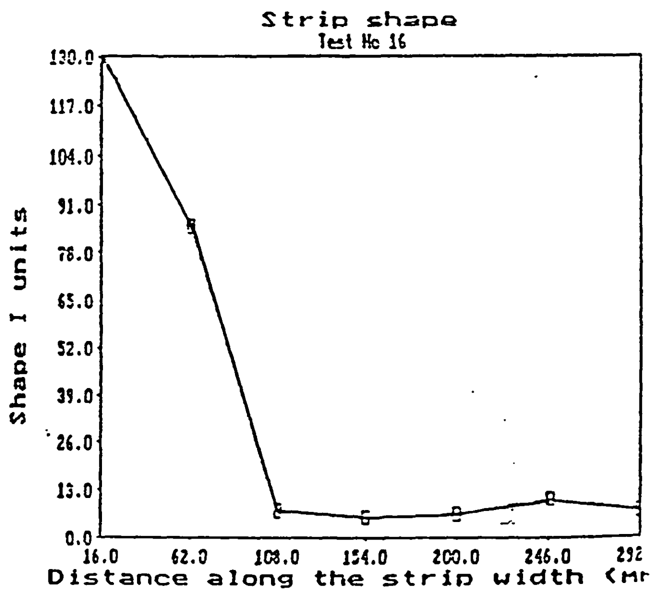
Strip shape
Test No 13
130.0
117.0
104.0
91.0
78.0
65.0
52.0
39.0
26.0
13.0
0.0
Shape I units
16.0
62.0
108.0
154.0
200.0
246.0
292.0
Distance along the strip width (mm)



Strip-shape
Test No 15
130.0
117.0
104.0
91.0
78.0
65.0
52.0
39.0
26.0
13.0
0.0
Shape I units
16.0
62.0
108.0
154.0
200.0
246.0
292
Distance along the strip width (m



Strip shape
Test No 14
130.0
117.0
104.0
91.0
78.0
65.0
52.0
39.0
26.0
13.0
0.0
Shape I units
16.0
62.0
108.0
154.0
200.0
246.0
292.0
Distance along the strip width (mm)

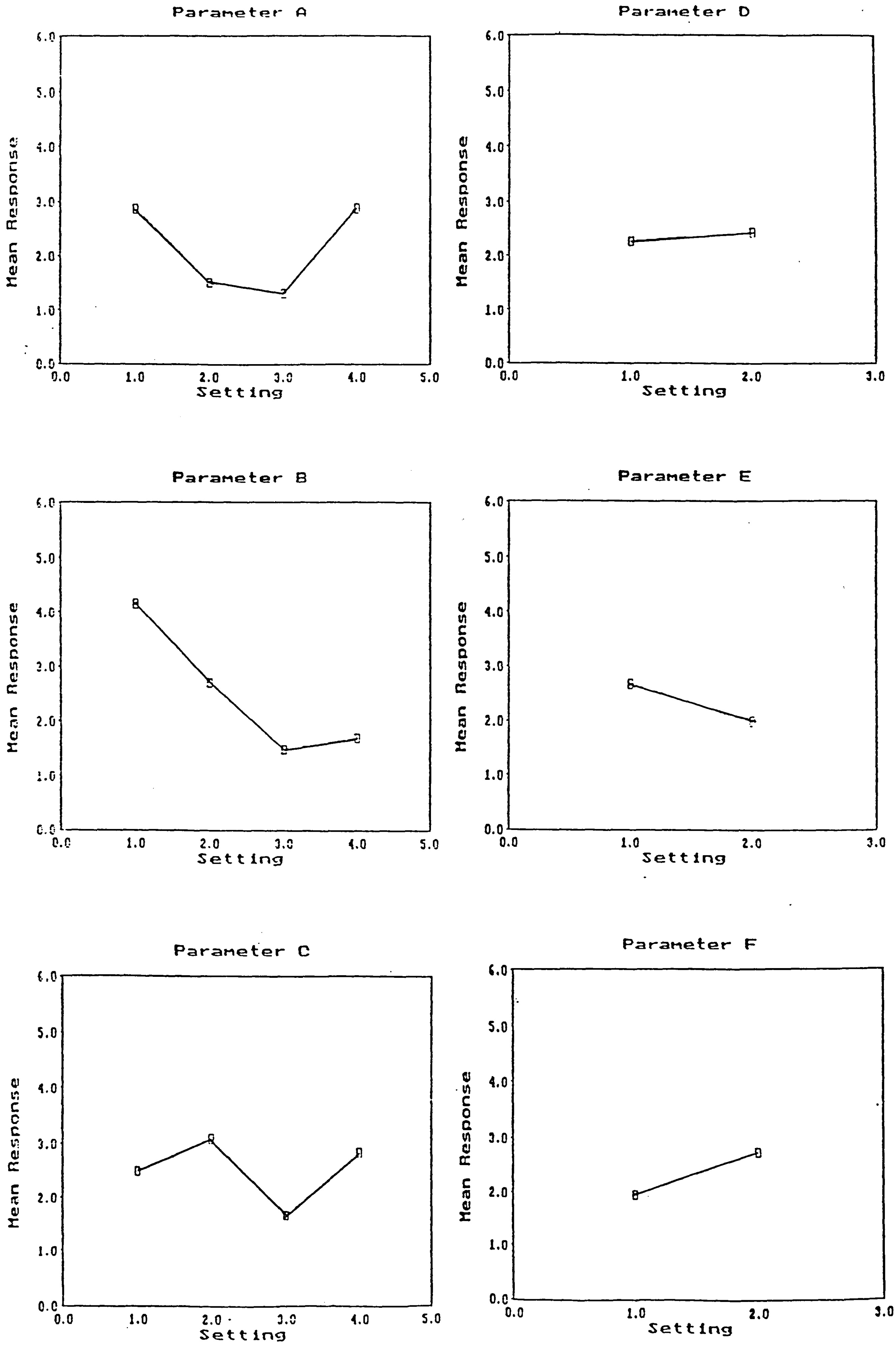


Strip shape
Test No 16
130.0
117.0
104.0
91.0
78.0
65.0
52.0
39.0
26.0
13.0
0.0
Shape I units
16.0
62.0
108.0
154.0
200.0
246.0
292
Distance along the strip width (m

Figure 21.

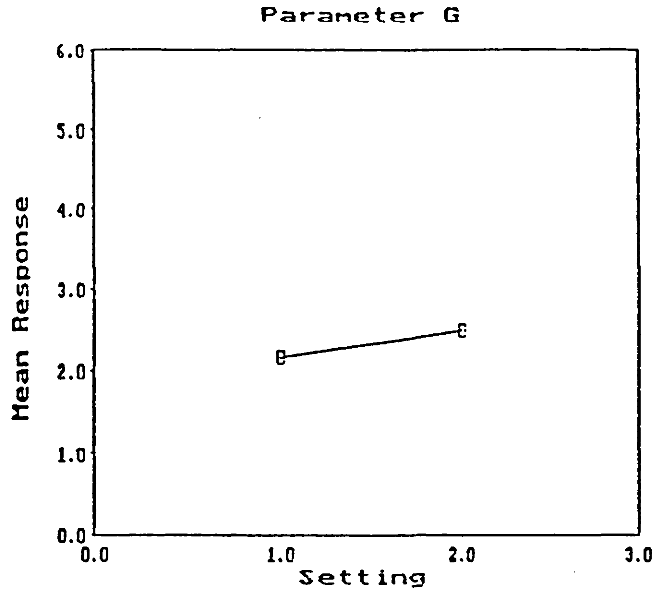
Mean Response Plots and Results for the Full Centre Strip Shape Defect. Measuring the Effects of Rolling Parameters on Strip Shape Throughout a Complete Rolling Sequence.

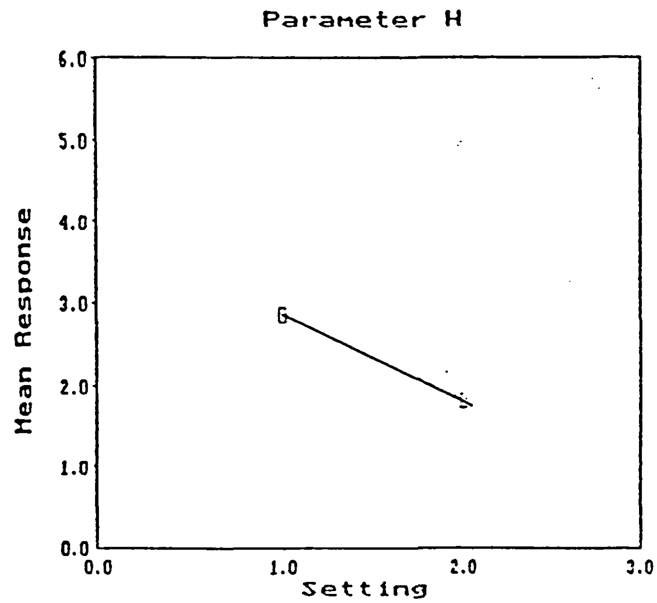
a



Parameter A
Parameter D
Parameter B
Parameter E
Parameter C
Parameter F
Mean Response
Setting
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Full centre measure mean respose





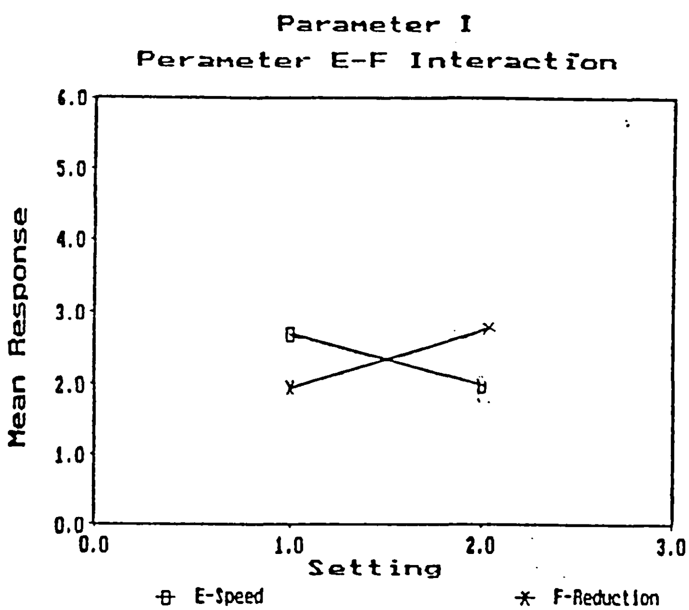
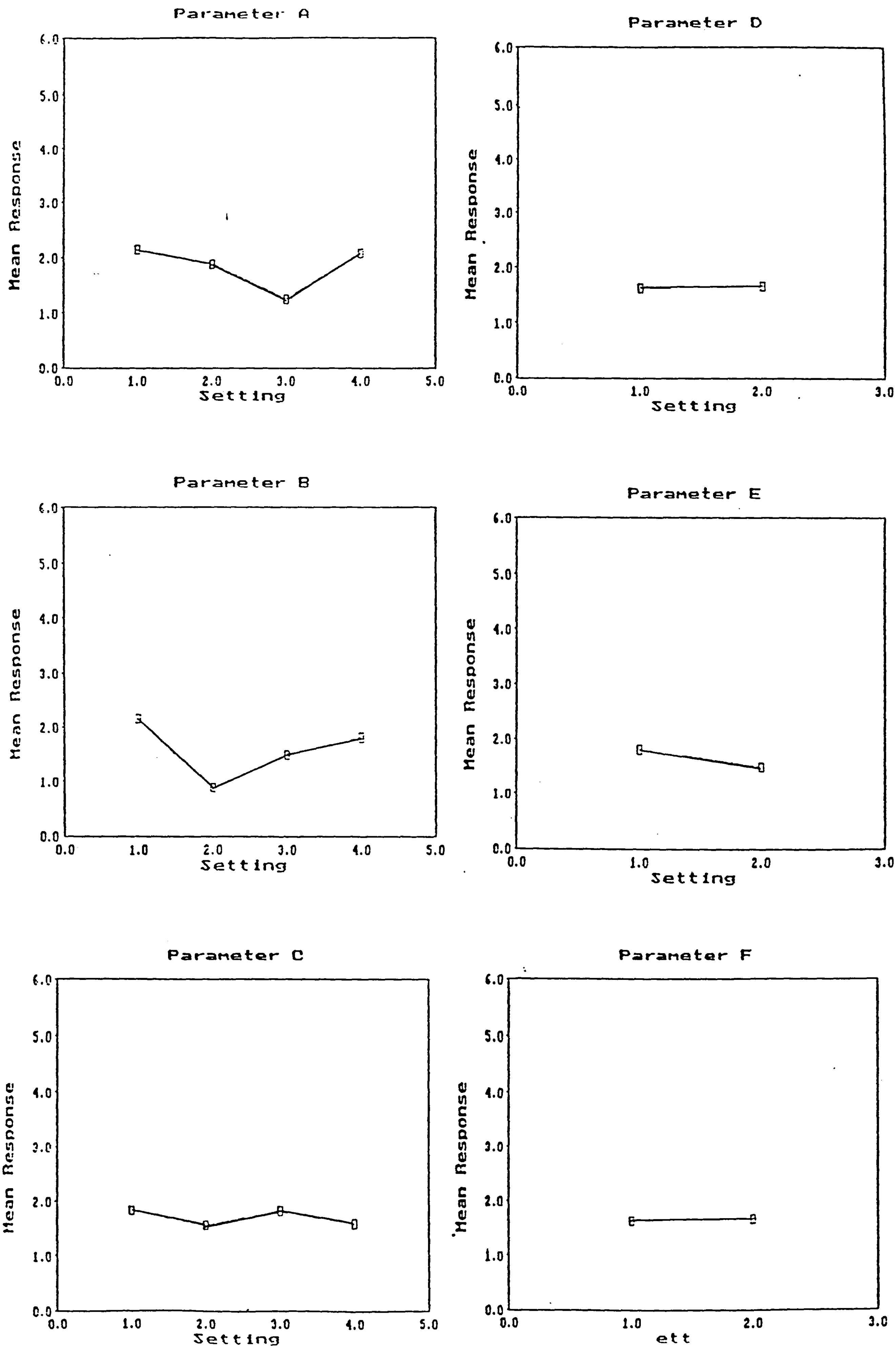
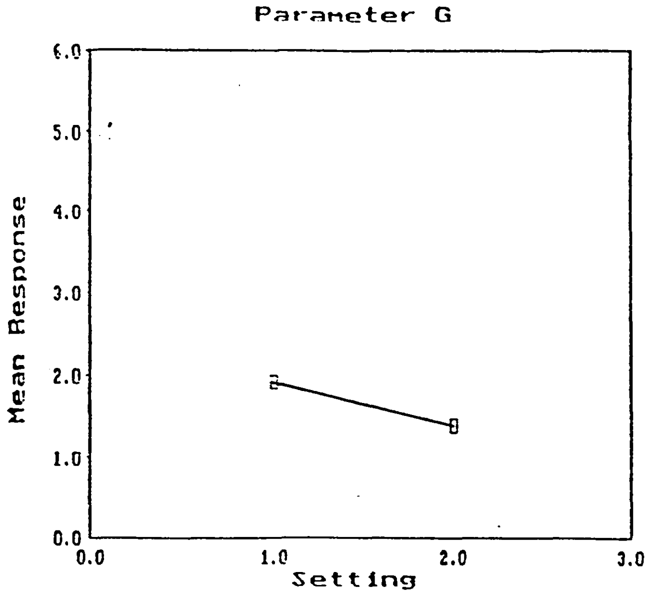


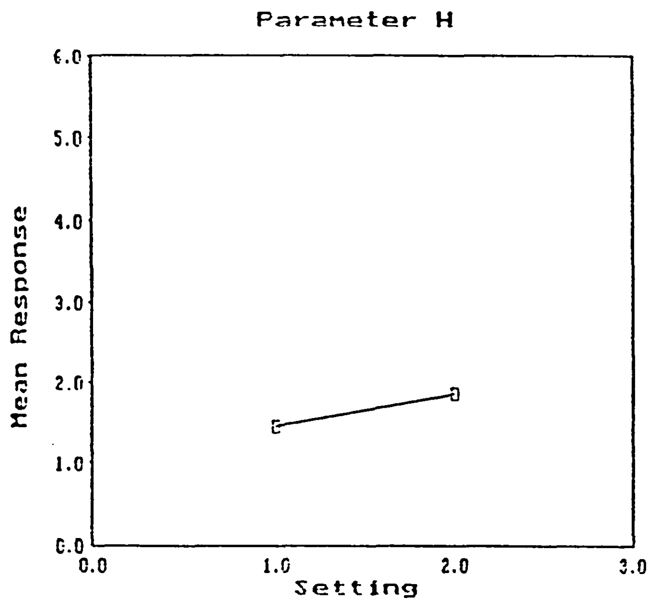
Figure 22.
Mean Response Plots and Results for the Average Measure Method of Recording Strip Shape. Measuring the Effects of Rolling Parameters on Strip Shape Throughout a Complete Rolling Sequence.

a


Parameter A
Parameter D
Parameter B
Parameter E
Parameter C
Parameter F
Mean Response
Setting
0.0
1.0
2.0
3.0
4.0
5.0
6.0
ett

Average shape measure mean response plots





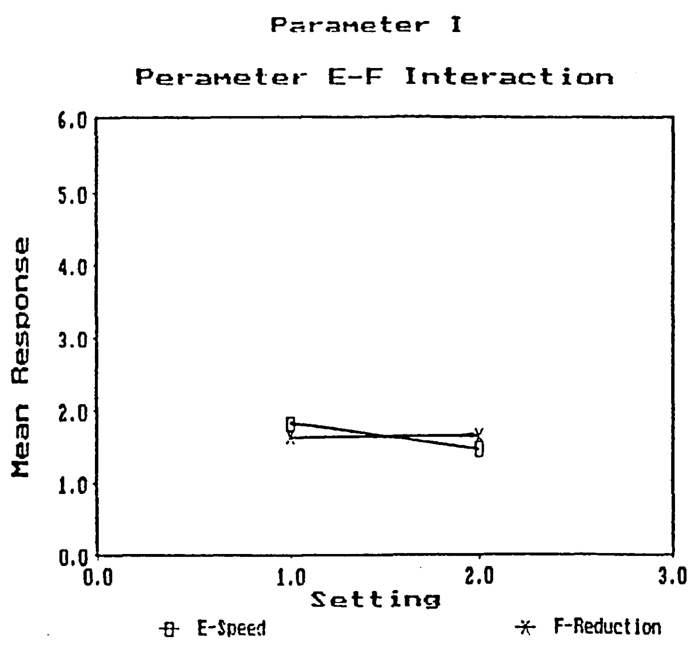
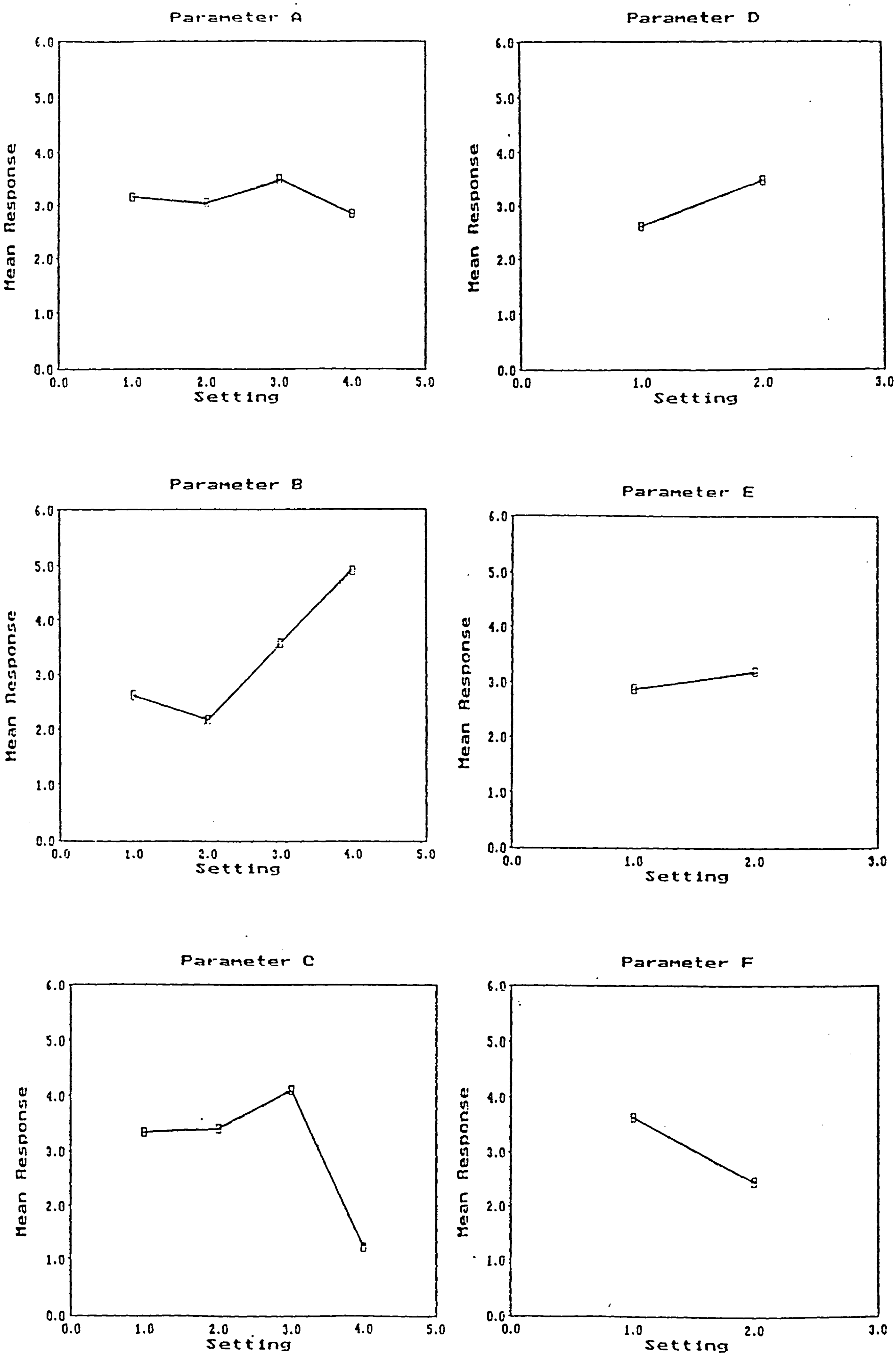


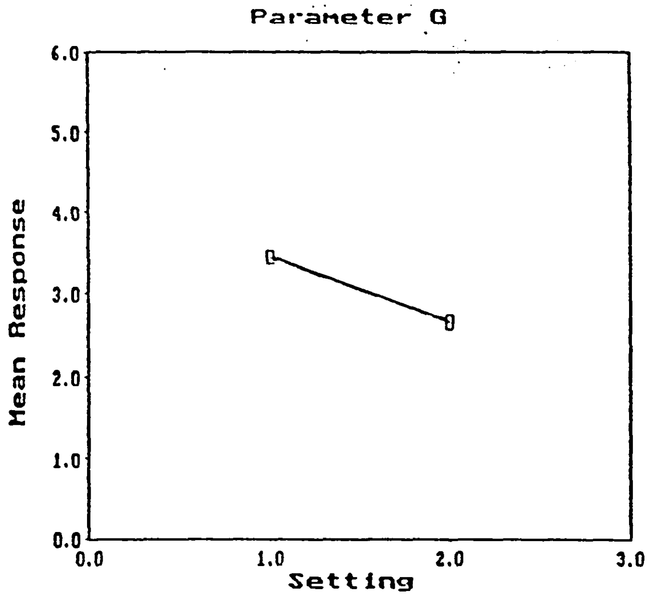
Figure 23.
Mean Response Plots and Results for the Wavy Edge Strip Shape Defect. Measuring the Effects of Rolling Parameters on Strip Shape Throughout a Complete Rolling Sequence.

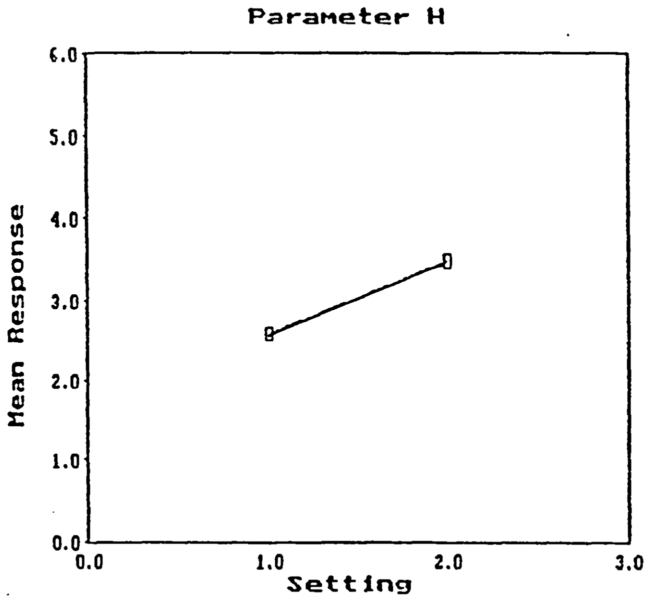
a


Parameter A
Parameter D
Parameter B
Parameter E
Parameter C
Parameter F
Mean Response
Setting
0.0
1.0
2.0
3.0
4.0
5.0
6.0

b

Loose edge measure mean response plots





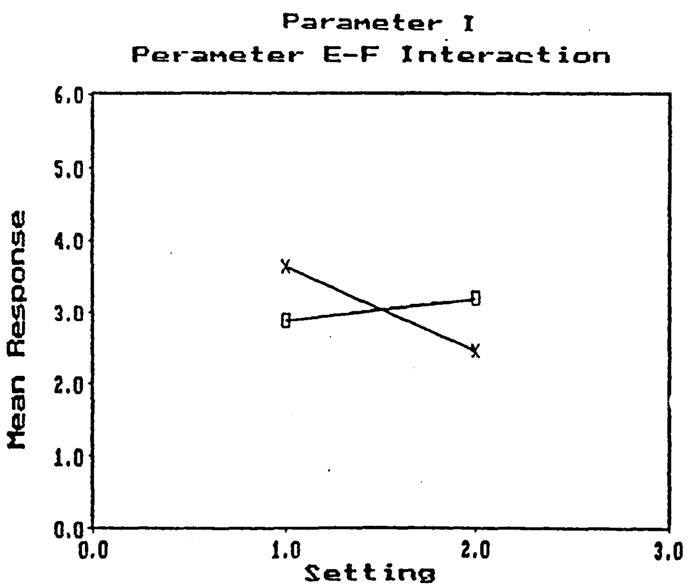
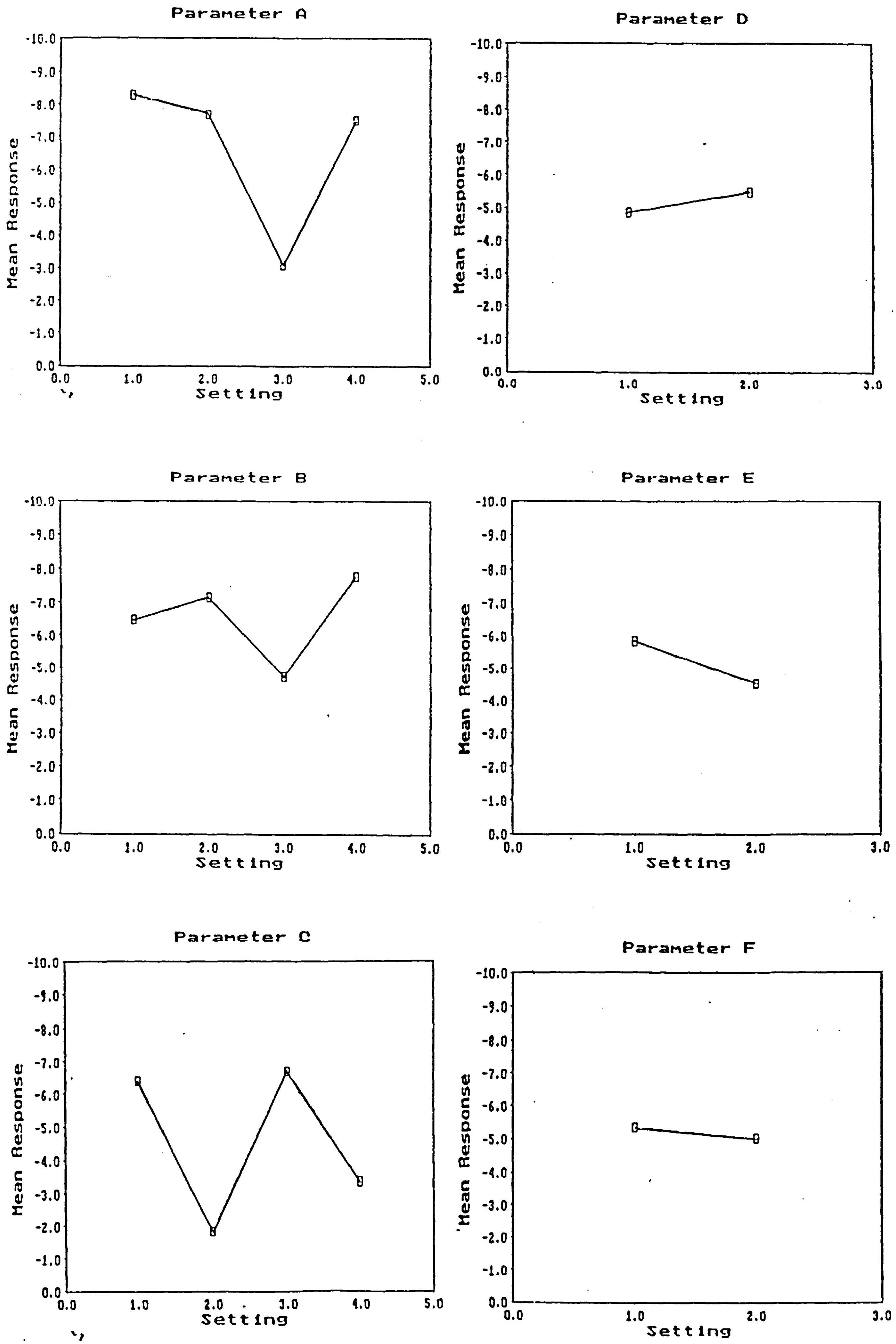


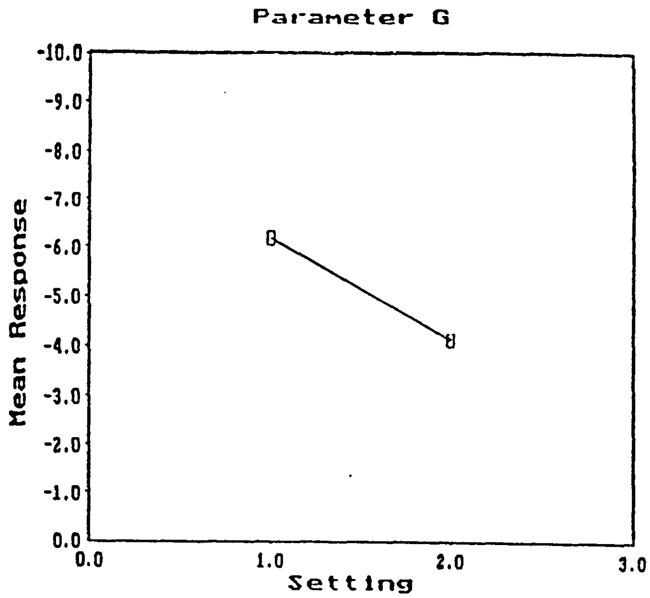
Figure 24.
Mean Response Plots and Results for the Signal to Noise Ratio. Measuring the Effects of Rolling Parameters on Strip Shape Throughout a complete Rolling Sequence.

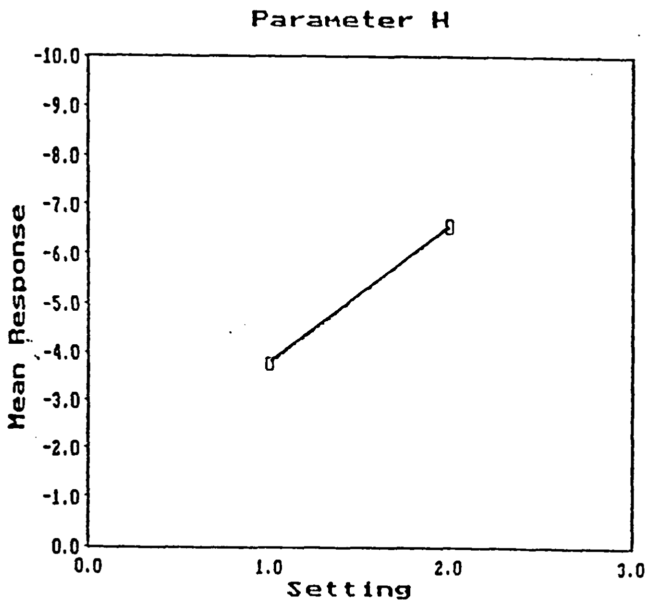
a



Parameter A
Mean Response
Setting
Parameter D
Mean Response
Setting
Parameter B
Mean Response
Setting
Parameter E
Mean Response
Setting
Parameter C
Mean Response
Setting
Parameter F
Mean Response
Setting

Signal to noise ratio mean response plots





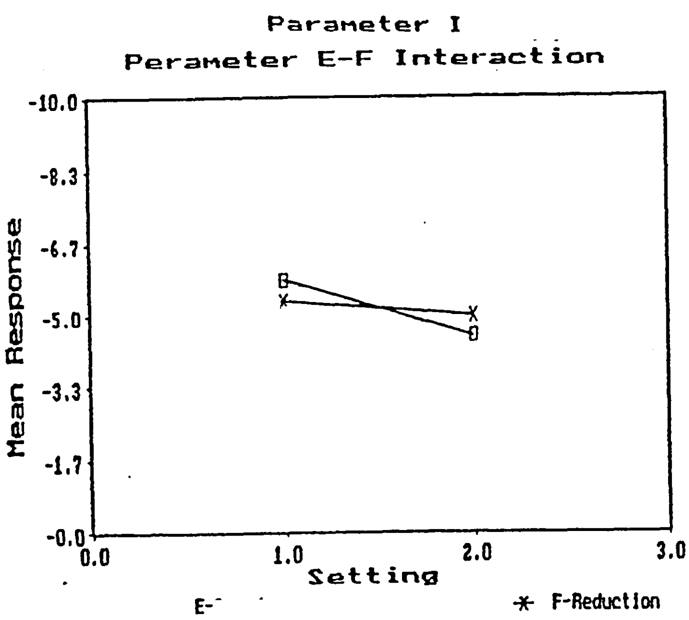
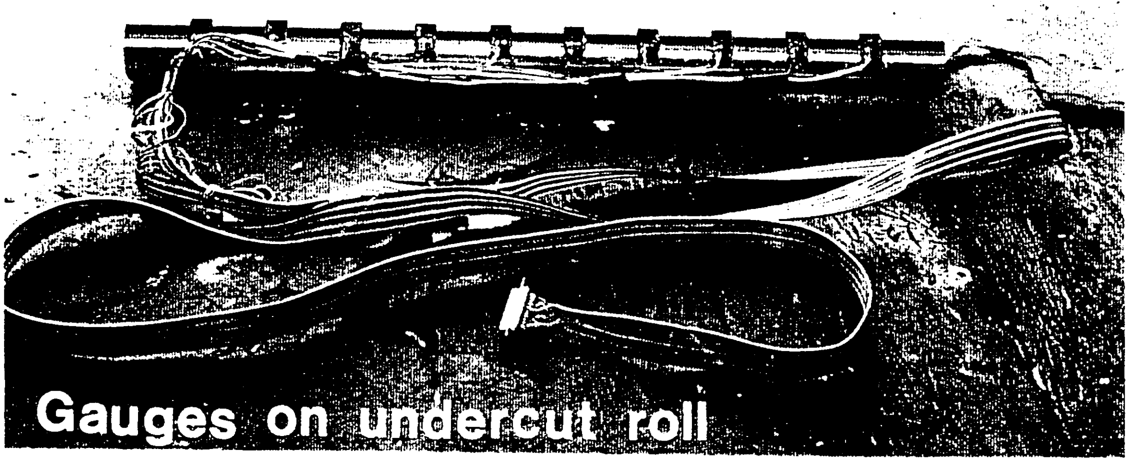


Figure 25.
Solatron Data Logger.
Used to Measure and Record the work
Roll Bending Strains.


Gauges on undercut roll

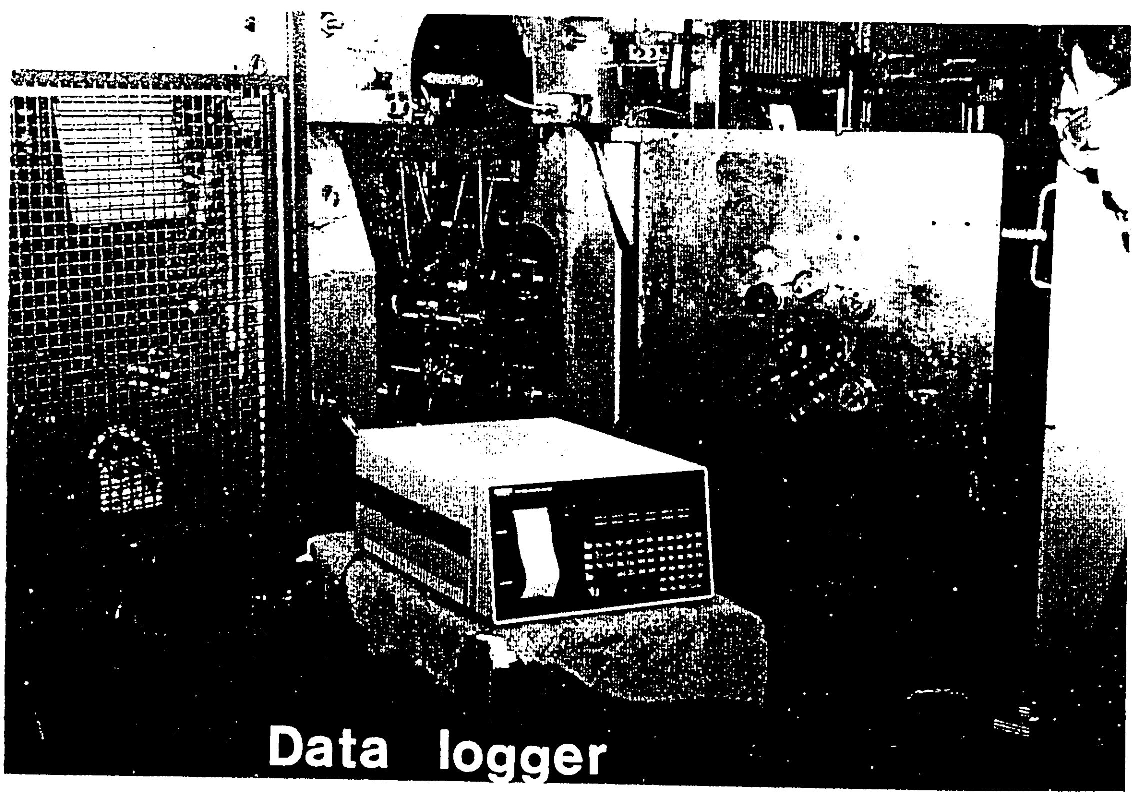

Data logger

Figure 26.
Strain Gauged Work Rolls with their Positions in the Roll Gap whilst Measuring Strains.

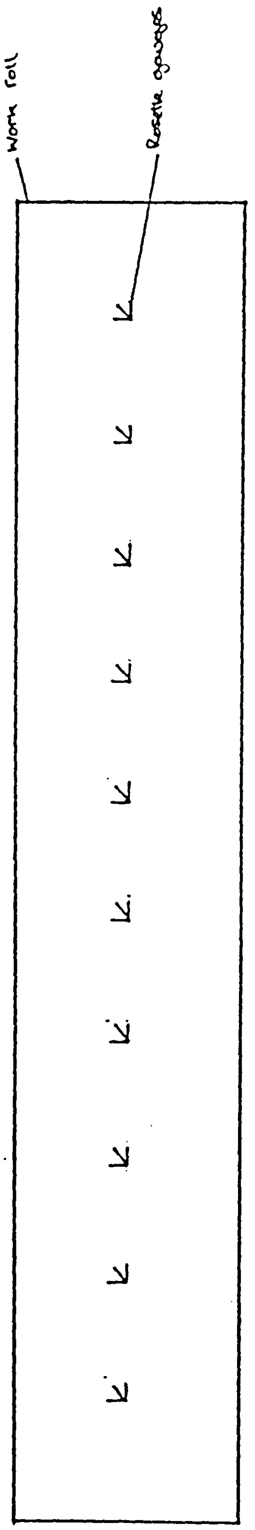
a) First (rosette) Gauged Roll.

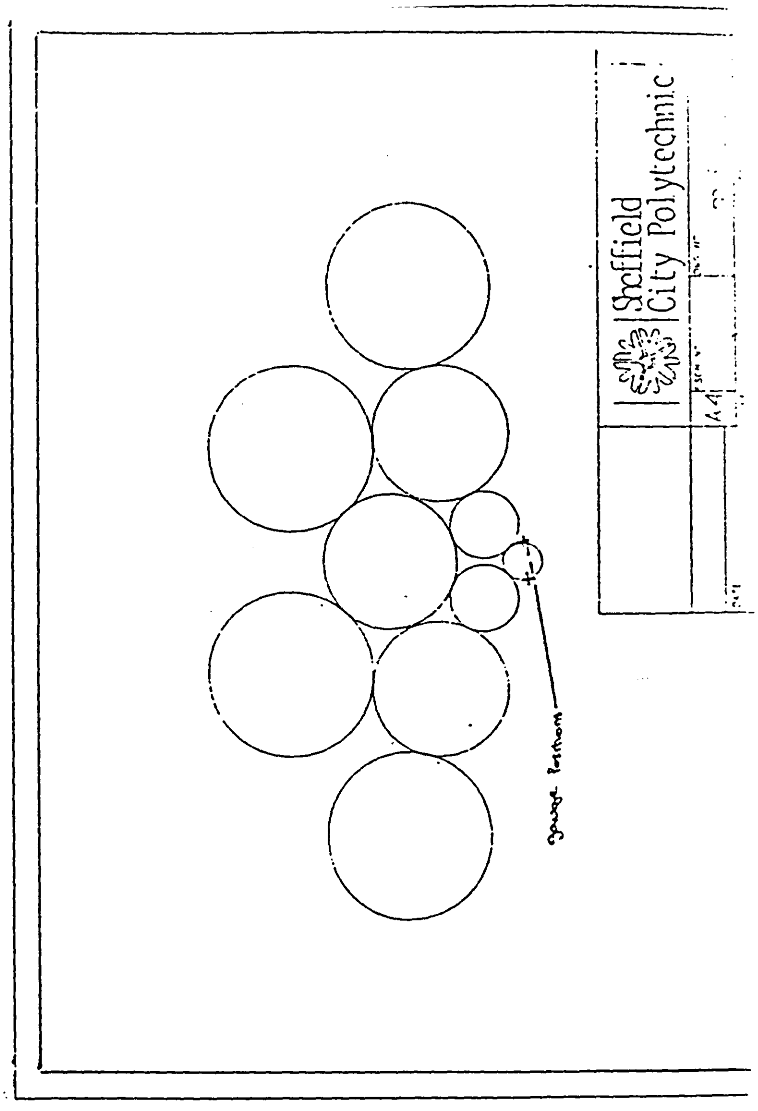
b) 180 Gauged Roll.

c) Undercut Gauged Roll.

First strain gauged work roll

a

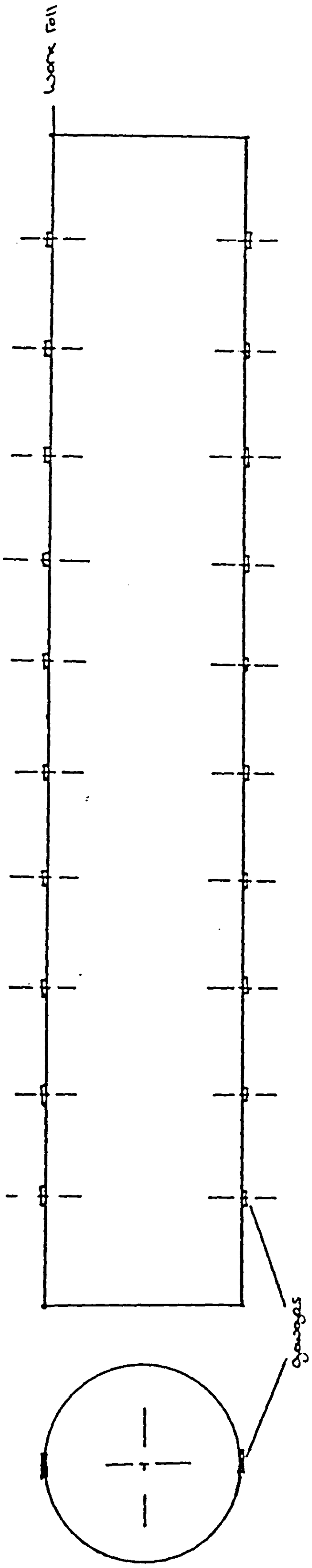


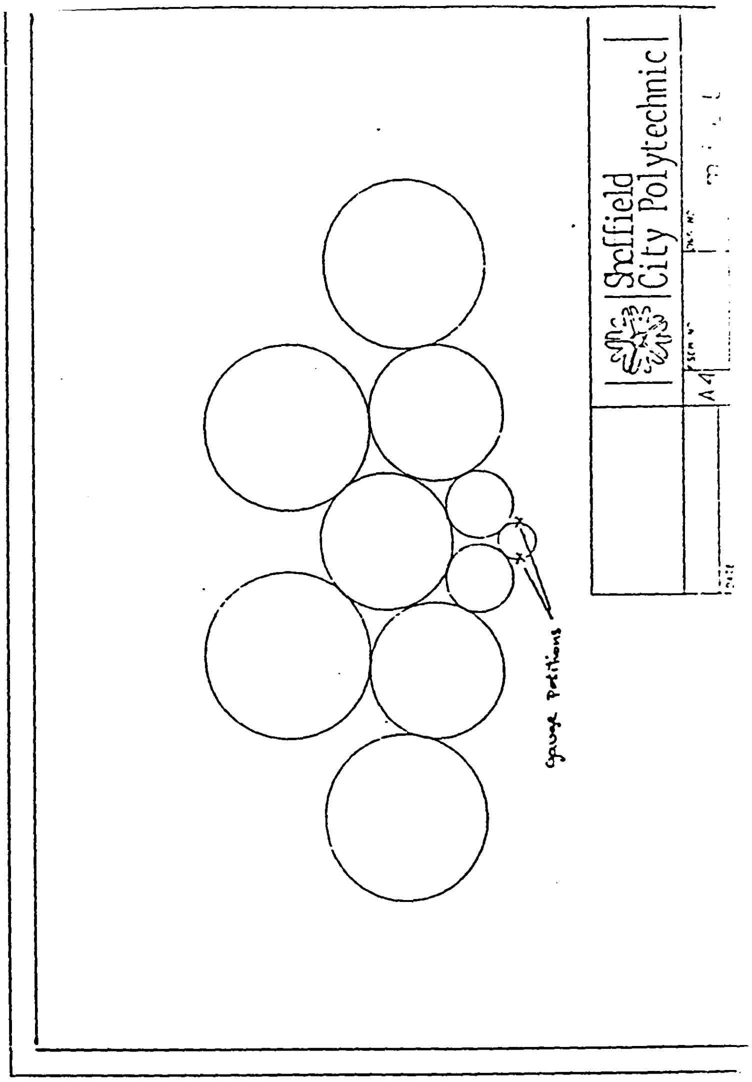


position of gauges in the roll gap

180 degree strain gauged work roll

b

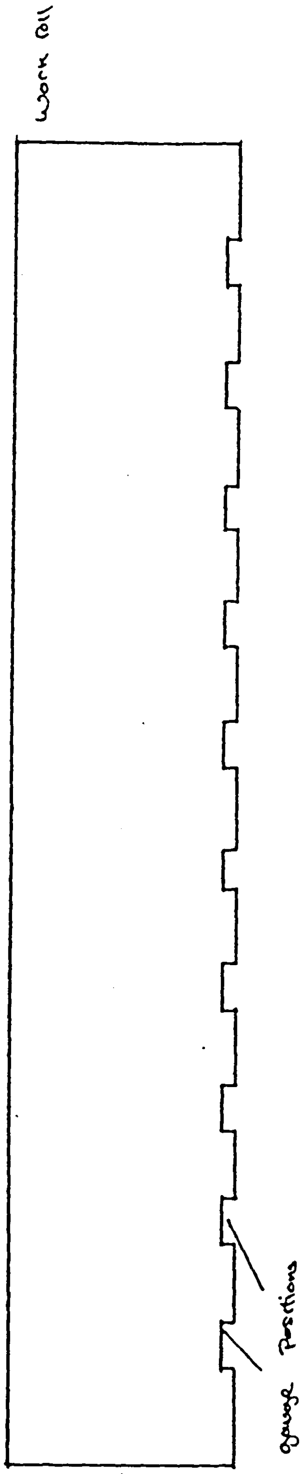


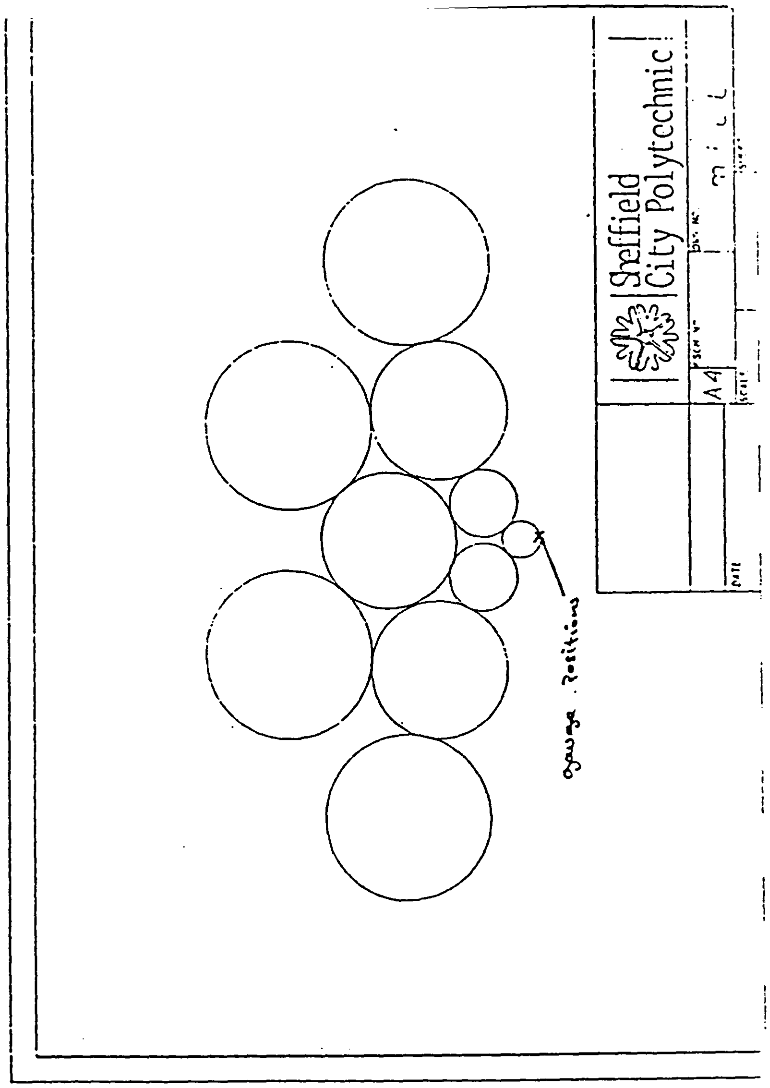


position of gauges in the roll gap

Undercut strain gauged work roll

C





position of gauges in the roll gap

Figure 27.
Strain Graphs Showing the Effects of First Intermediate Roll Position on Work Roll Strain.

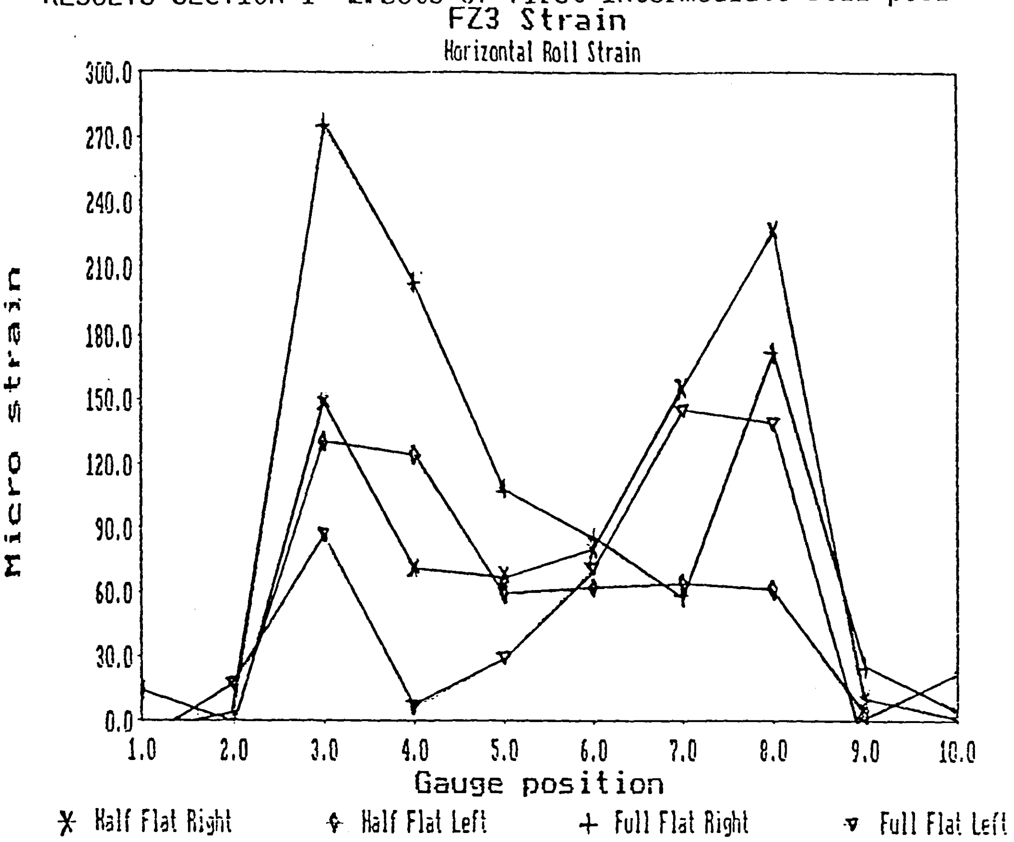
a) Horizontal Roll Strains.

b) Vertical Roll Strains.

c) Undercut Roll Strains.

a

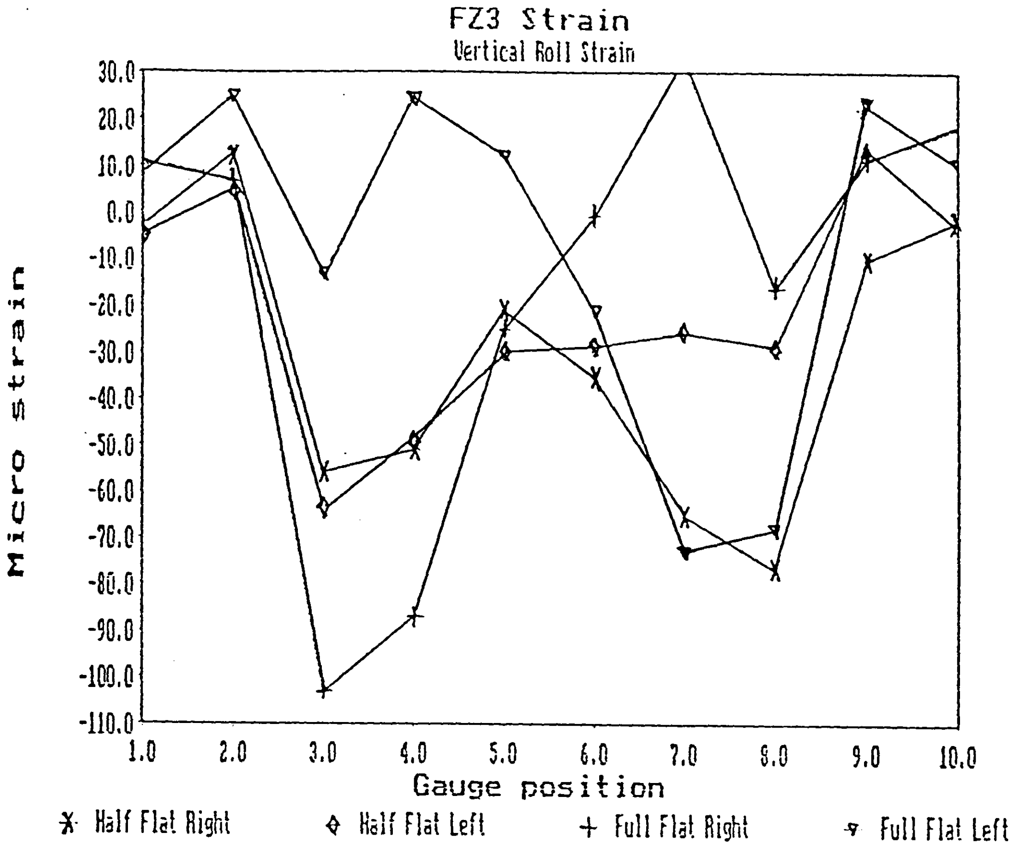
RESULTS SECTION 1 EFFects of first intermediate roll position



7" First intermediate rolls
Two flat work rolls
Top mill position
100 Ton load
Strip in

Full/Half flat = Position of the first intermediate rolls
Right/Left = Position of the gauges in the mill

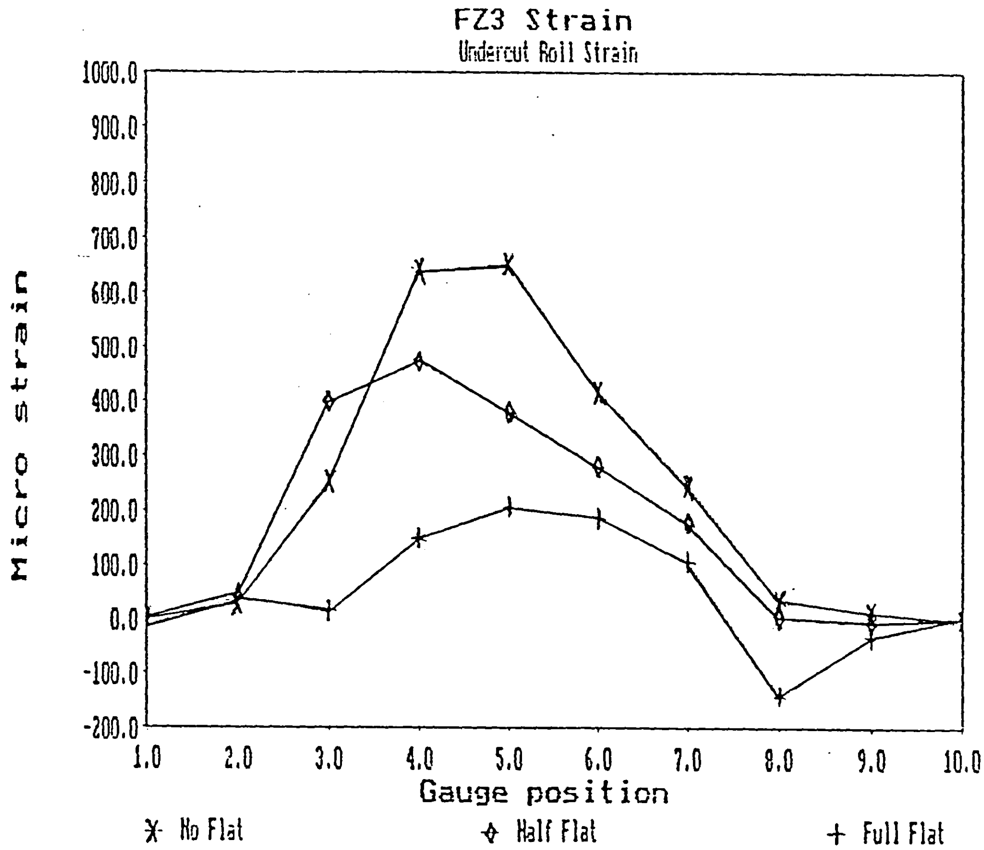
b



7" Taperd first intermediate rolls
Two flat work rolls
Top Mill position
100 ton load
Strip in

Full/Half flat = Position of the first intermediate rolls
Right/Left = Position of the gauges in the mill

C



7" Taperd First intermediate rolls
Two flat work rolls
Top mill position
100 Ton load
Strip in

Full/Half flat = Position of the first intermediate rolls
Right/Left = Position of the gauges in the4 mill

Figure 28.
Strain Graphs Showing the Effects of First Intermediate Roll Profile on Work Roll Strain.

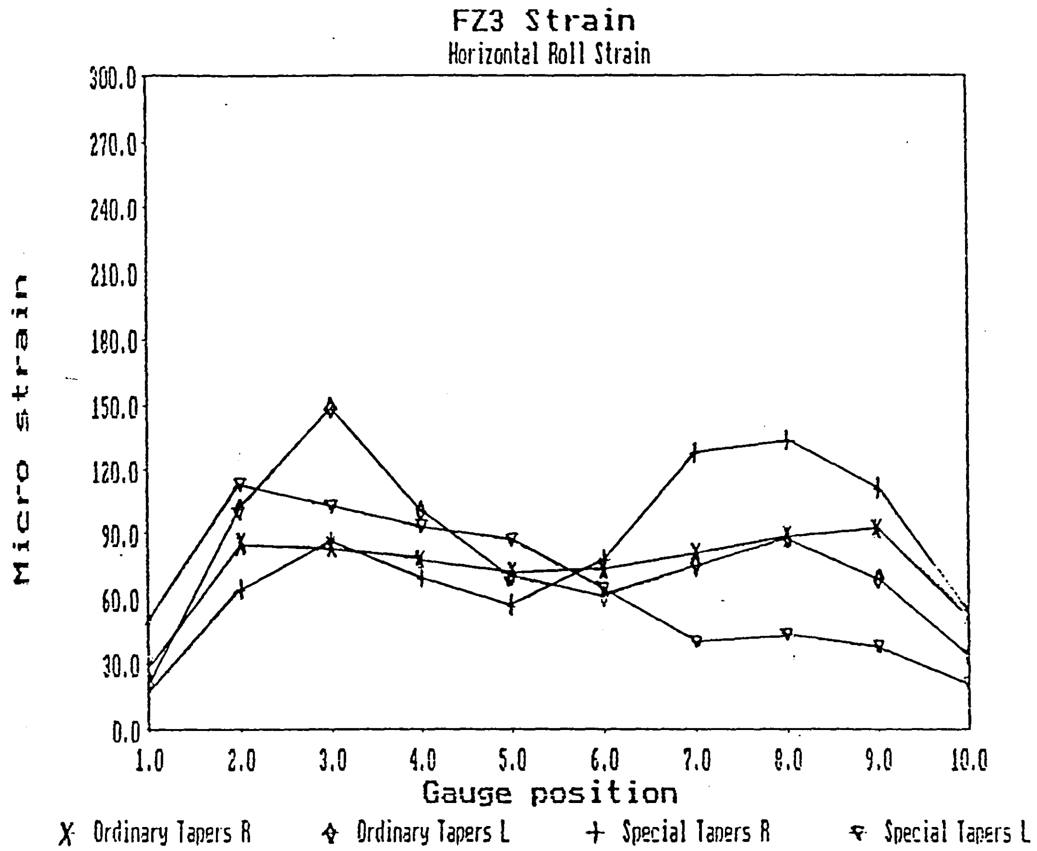
a) Horizontal Roll Strains.

b) Vertical Roll Strains.

c) Undercut Roll Strains.

Effects of first intermediate roll profile

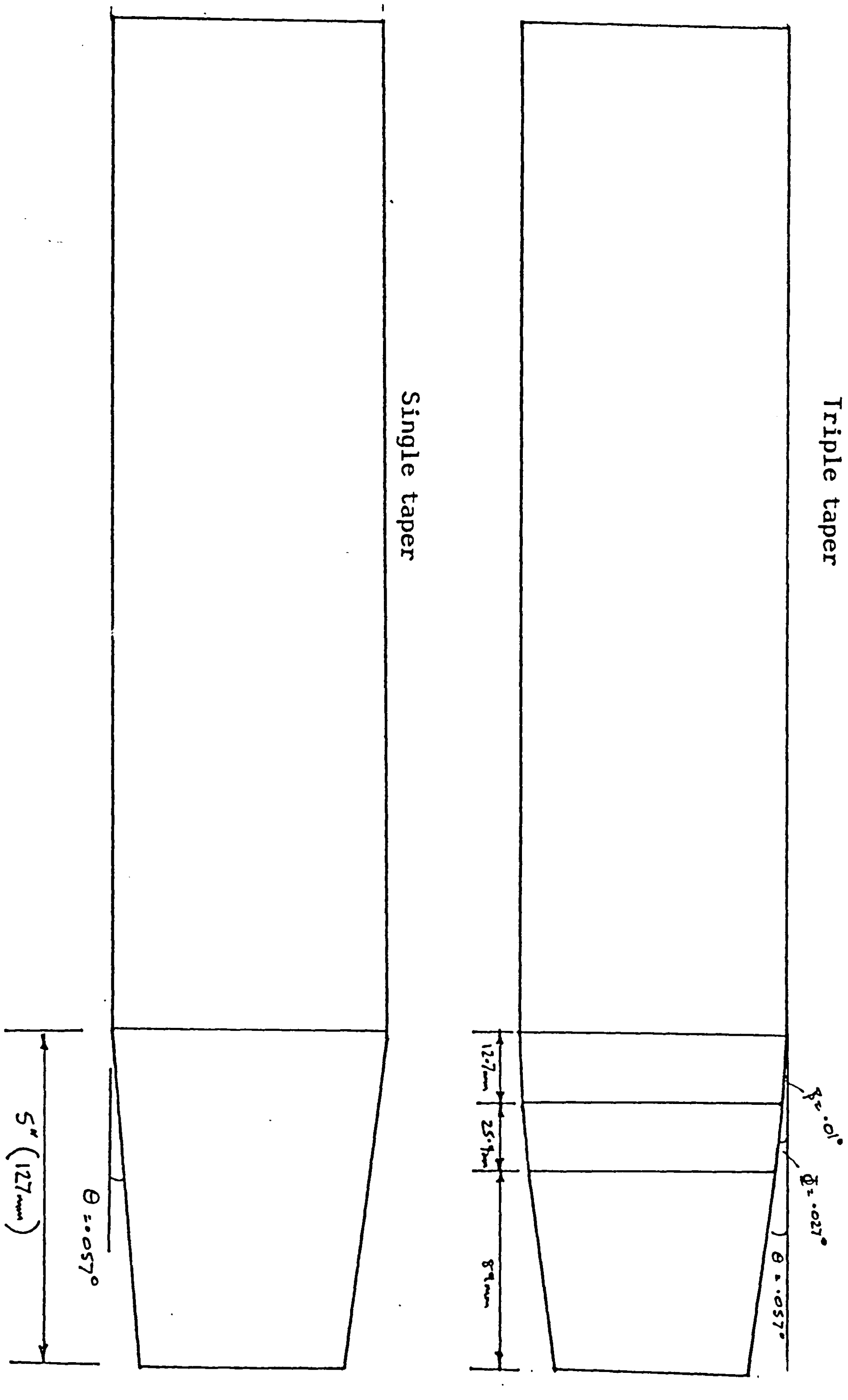
a



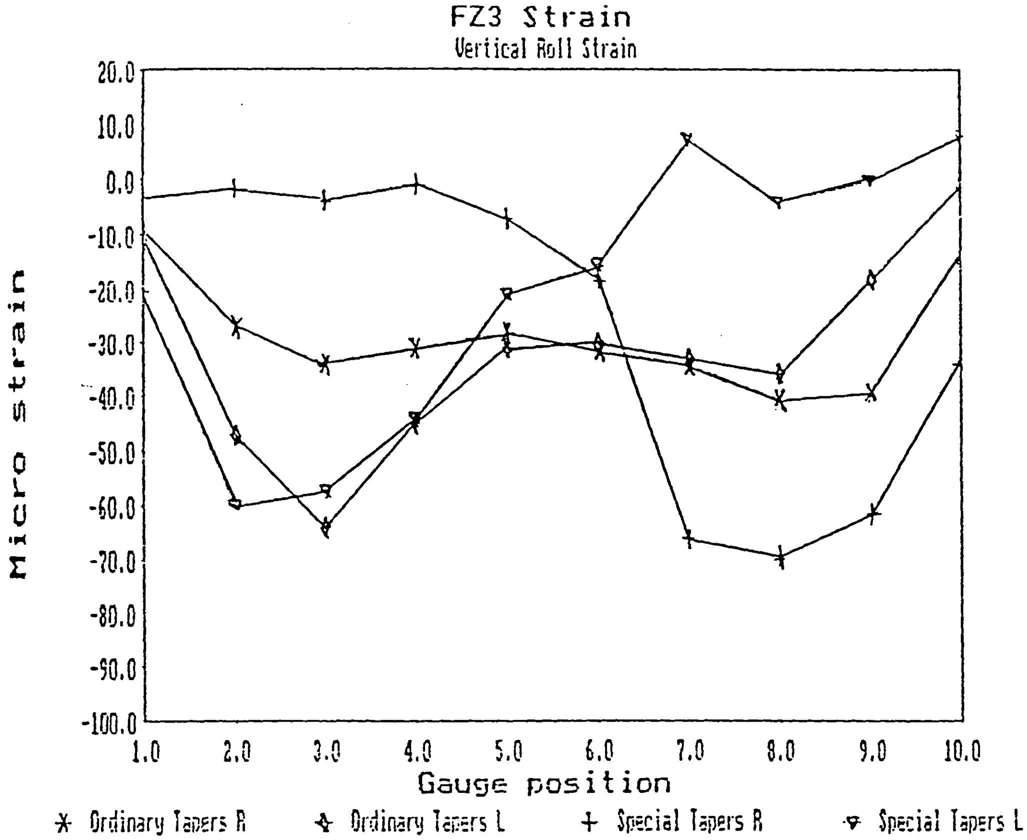
5" Taperd First intermedeate rolls
1/2 Flat taper position
Two flat work rolls
Top mill position
100Ton load
No strip in

= Left of the mill gauge position
= Right of the mill gauge position

First intermediate roll profiles



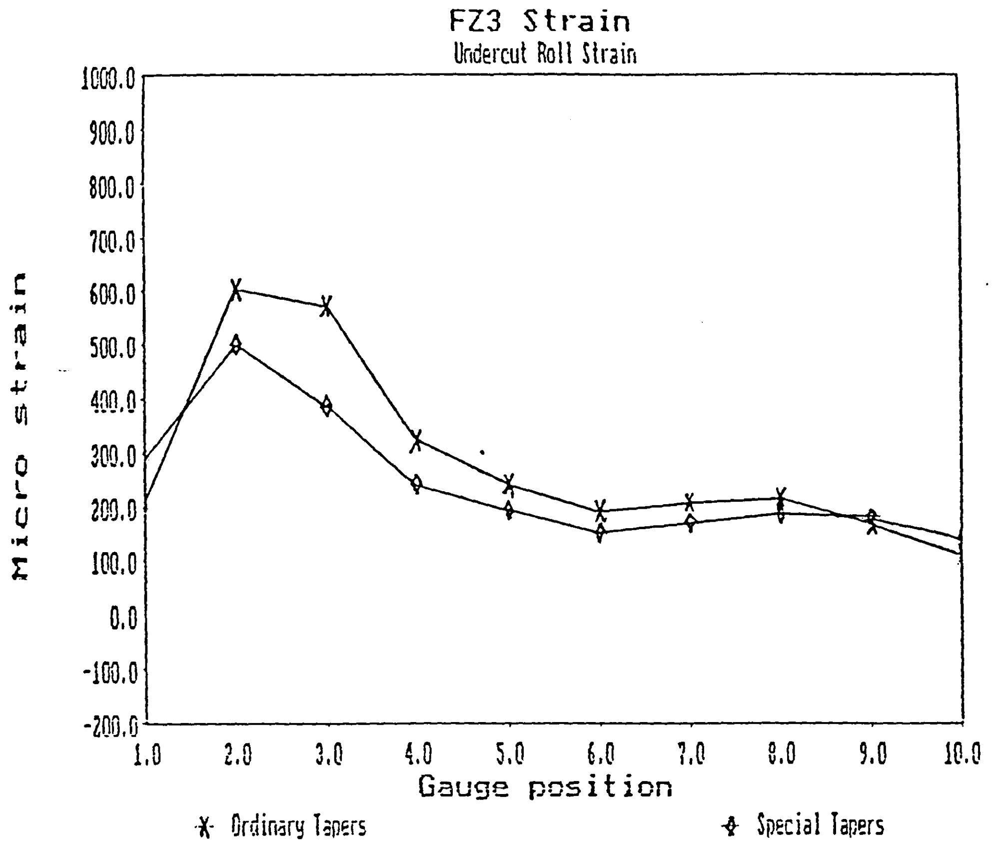
b



5" Taperd first intermediate rolls
1/2 Flat taper position
Two flat work rolls
Top mill position
100 Ton load
No strip in

L = Left of the mill gauge position
R = Right of the mill gauge position

C



5" Taperd first intermediate rolls

1/2 Flat ta-er ppeition
Two flat work rolls
Top mill position
100 Ton load
No strap in

1 = Left of the mill gauge position
R = Right of the mill gauge position

Figure 29.

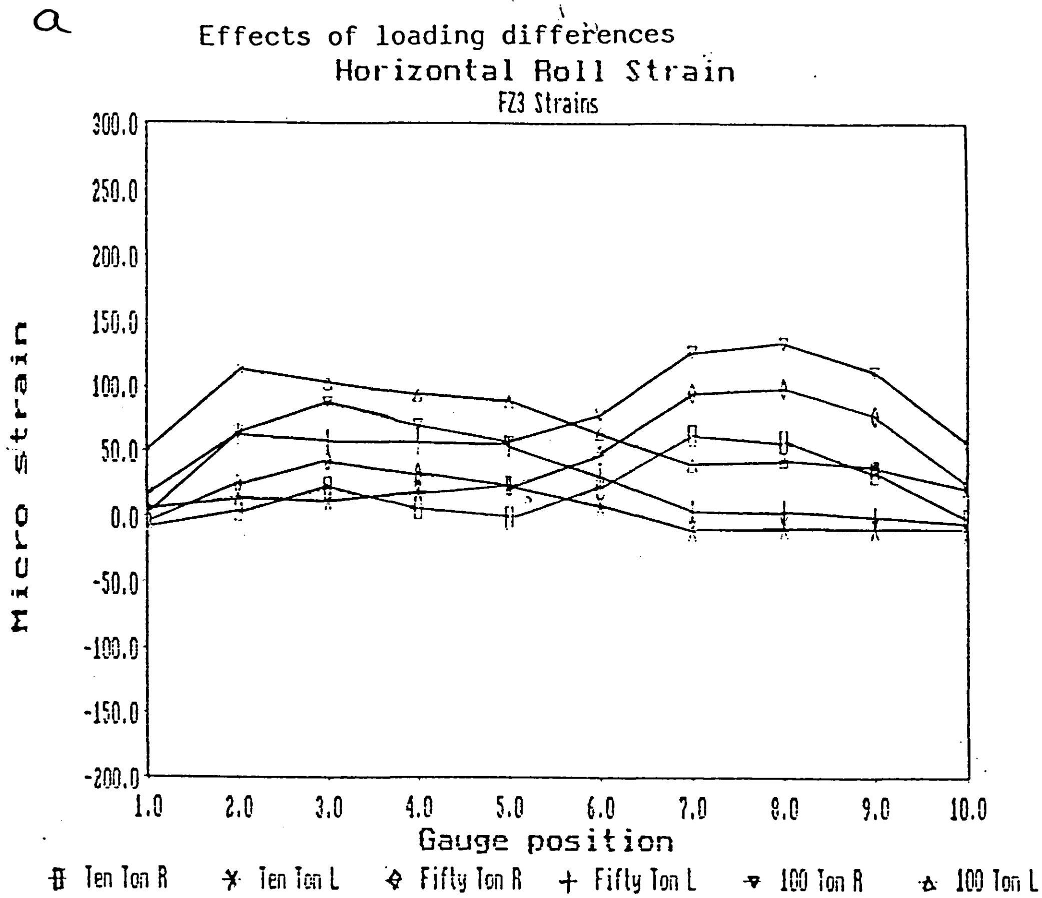
Strain Graphs Showing the Effects of Loading Differences on Work Roll Strain.

a) Horizontal Roll Strain.

b) Vertical Roll Strain.

c) Undercut Roll Strain.

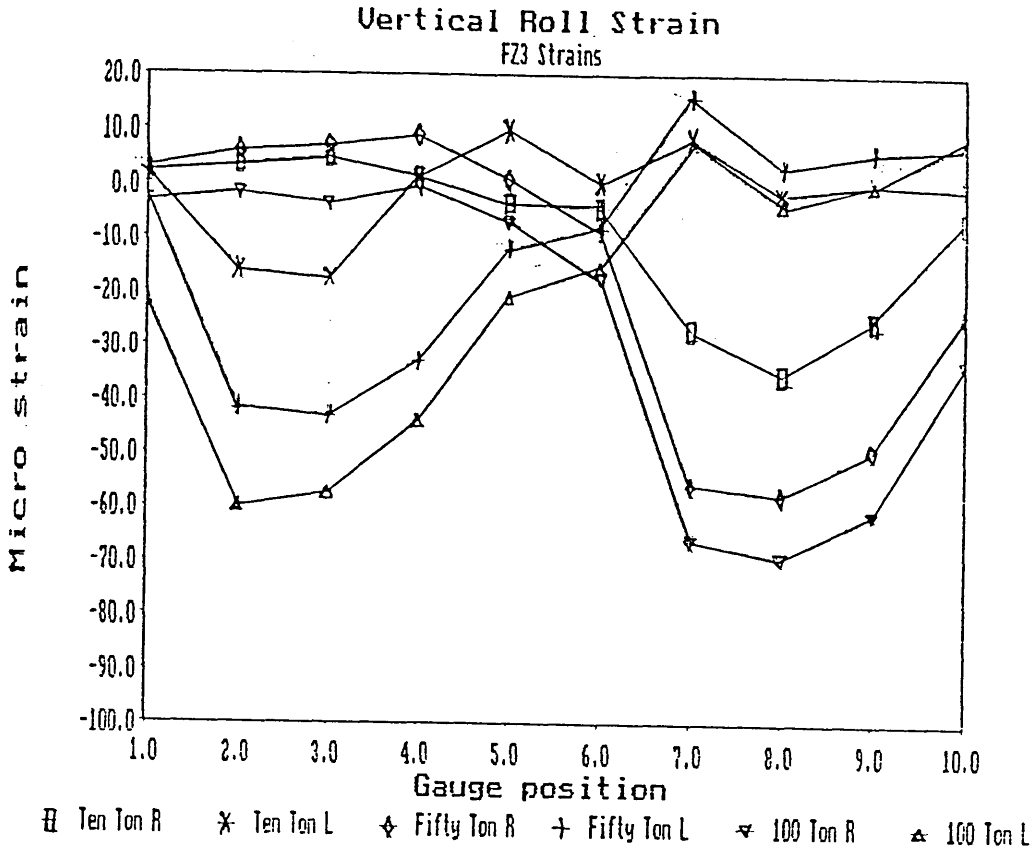
a



5" Special tapers
1/2 Flat taper position
Two flat work rolls
Top mill position
No strip in

L = Left of the mill gauge position
R = Right of the mill gauge position

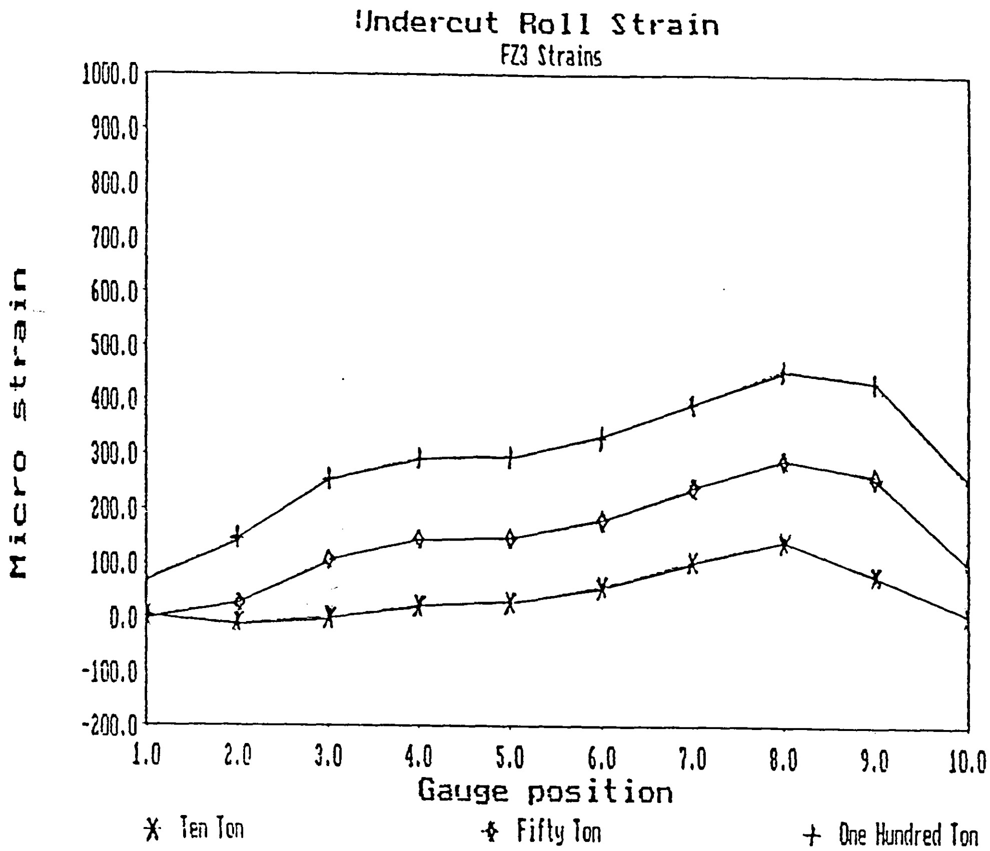
b



5" Special taperd first intermediate rolls
1/2 Flat taper position
Two flat work rolls
Top mill position
No strip in

L = left of the mill gauge position
R = Right of the mill gauge position

C



5" Special taperd first intermediate rolls
1/2 Blat taper position
Two flat work rollls
No strip in

L== Left of the mill gauge position
R = Right of the mill gauge position

Figure 30.
Strain Graphs Showing the Effects of Strip in or Strip out of the Roll Gap on Work Roll Strain.

a) Horizontal Roll Strain.

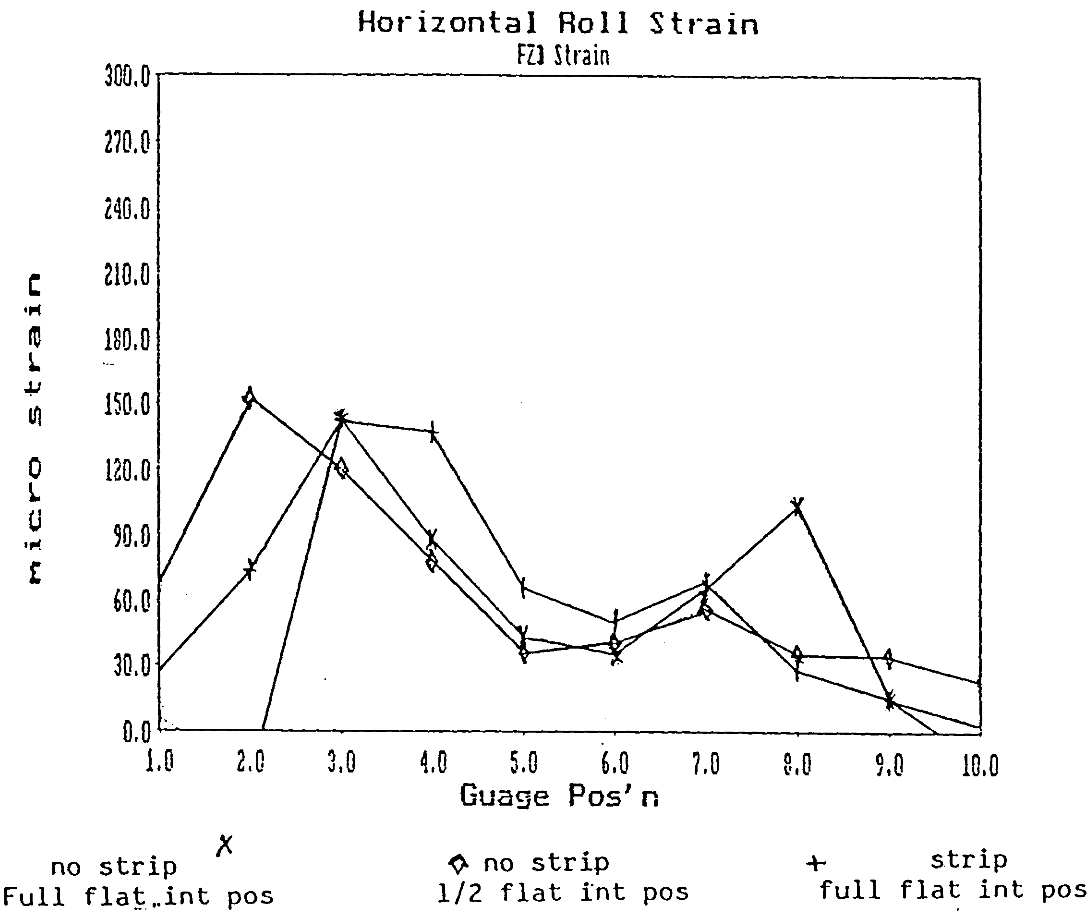
b) Horizontal Roll Strain.

c) Vertical Roll Strain.

d) Undercut Roll Strain.

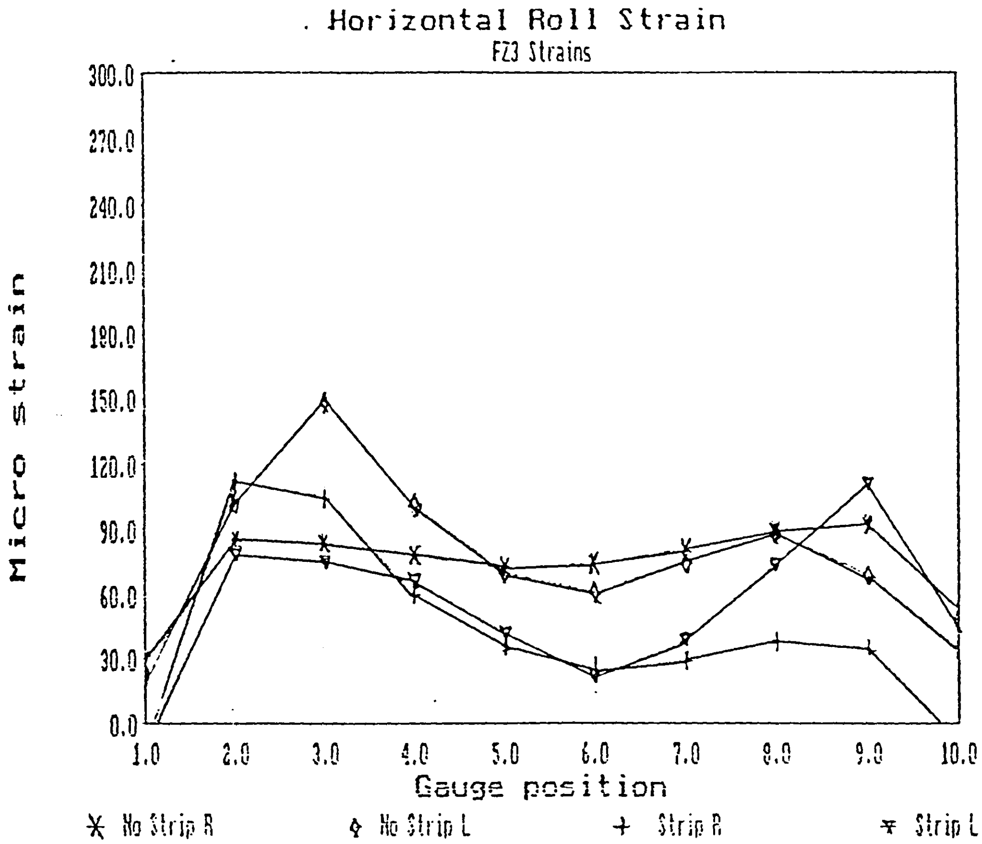
a

Effects of strip in/out of the roll bite



7" taperd first intermediate rolls
Two flat work rolls
Top mill position
100 Ton load

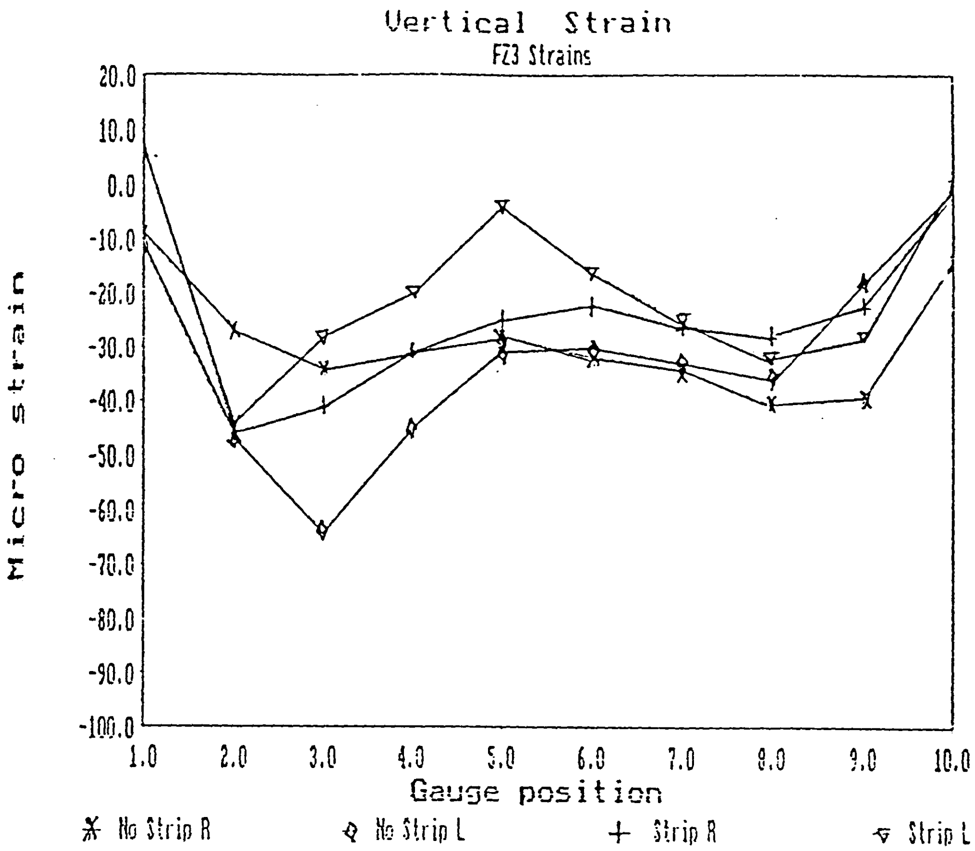
b



5" Taperd first intermediate rolls
1/2 flat taper position
Two flat work rolls
Top mill position
100 Ton load

L = Left of the mill gauge position
R = Right of the mill gauge position

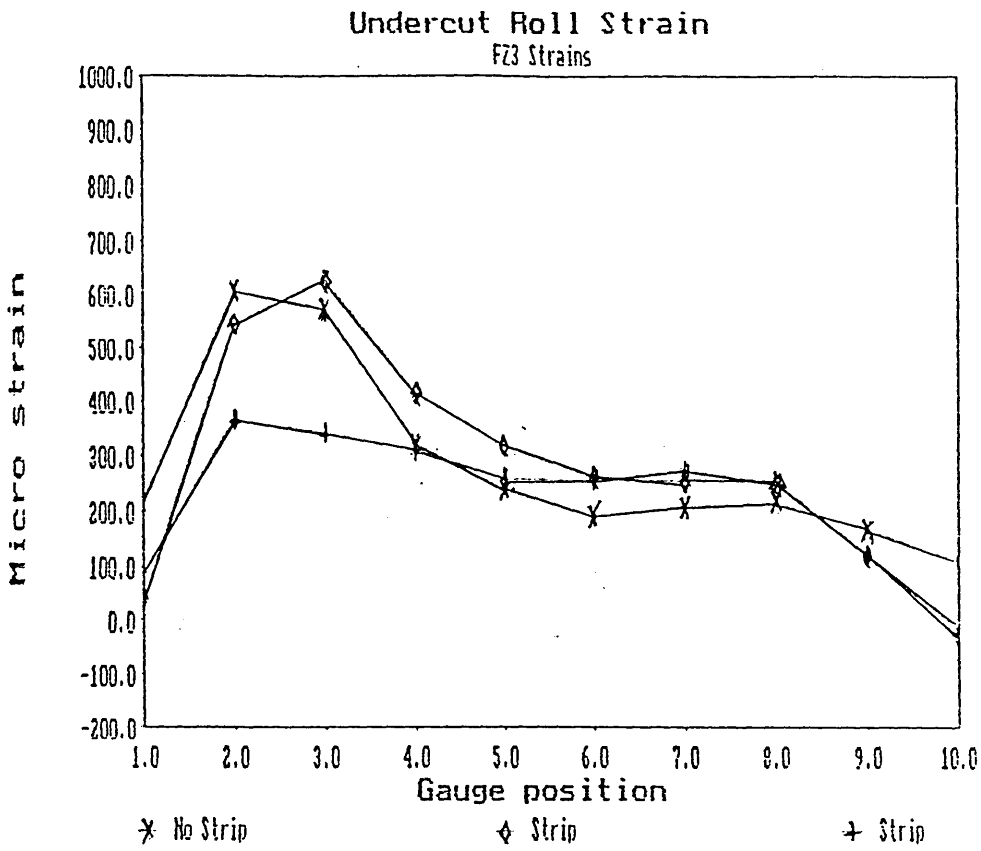
C



5" Taperd first intermediate rolls
1/2 Flat taper position
Two flat work rolls
Top mill position
100 ton load

L = Left of the mill gauge position
R = Right of the mill gauge position

d



5" taperd first intermediate rolls
1/2 Flat taper position
Two flat work rolls
Top mill position
100 Ton load

Figure 31.

Strain Graphs Showing the Effects of Work Roll Profile Differences on Work Roll Strain.

a) Horizontal Roll Strain.

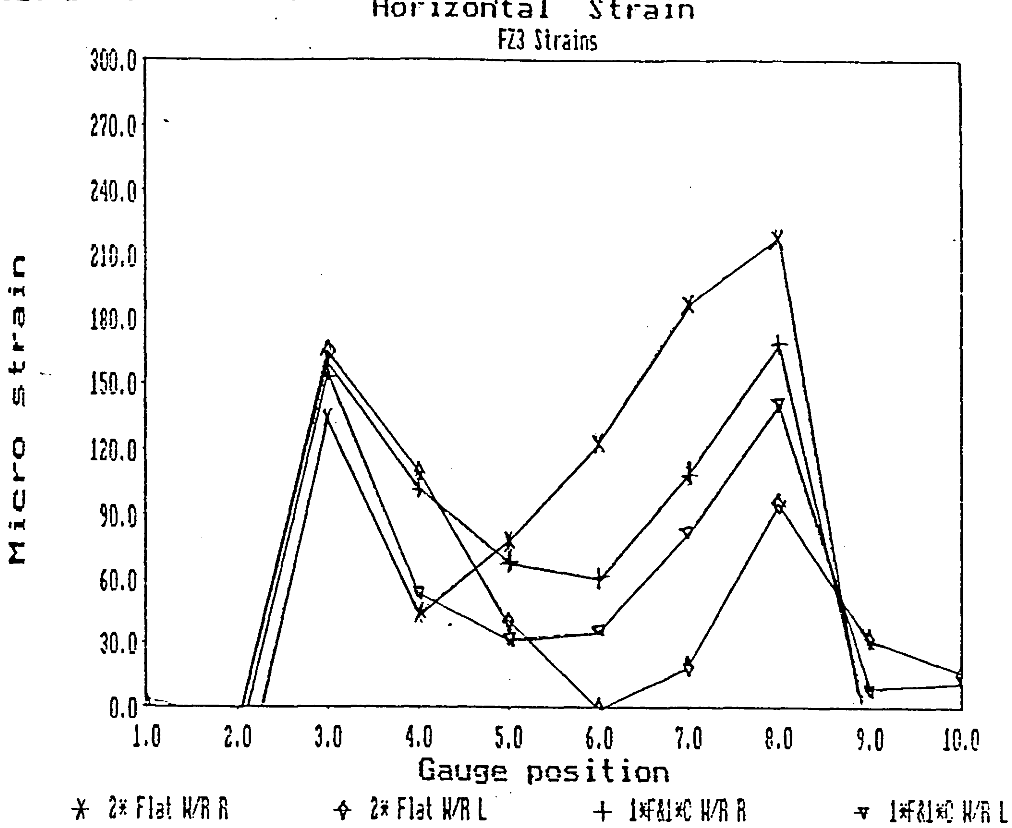
b) Vertical Roll Strain.

c) Undercut Roll Strain.

d) Undercut Roll Strain.

a

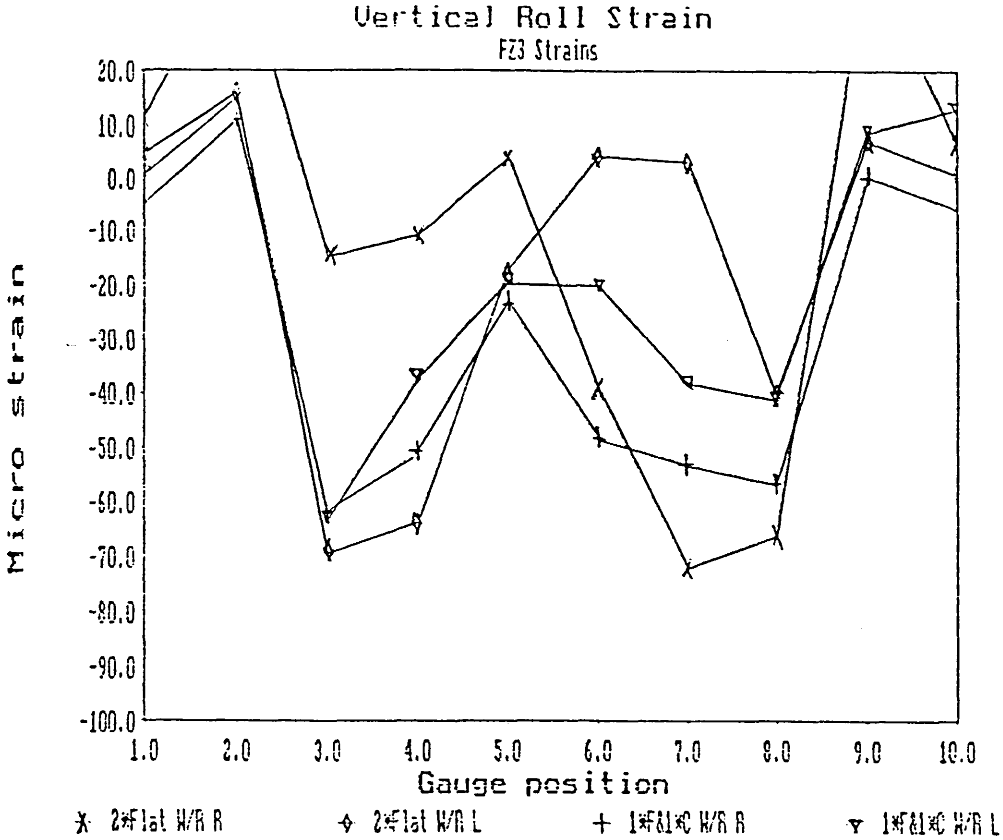
RESULTS SECTION 5 Effects of work roll profile



7"Special taperd first intermediate rolls
1/2 Flat taper position
Top mill position
100 Ton Load
Strip in

L = Left of the mill gauge position
R = Right of the mill gauge position
W/R = Work rolls

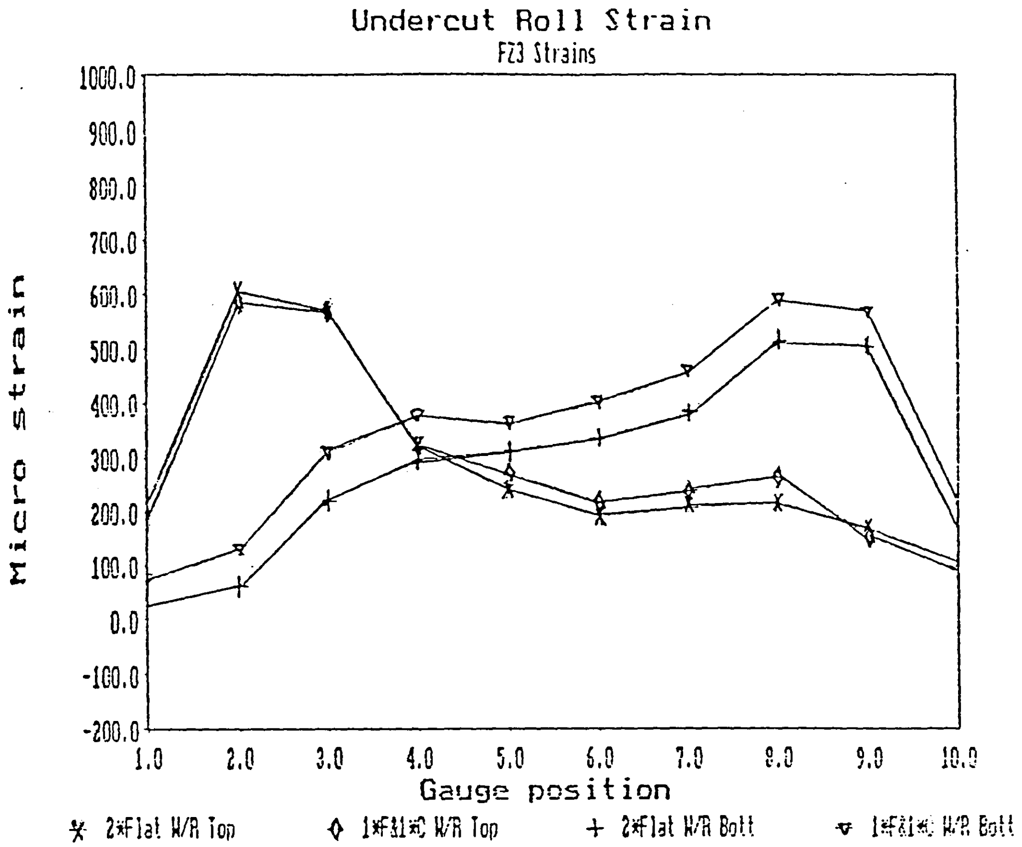
b



7" Special taperd first intermediate rolls
1/2 Flat taper position
Top mill position
100 Ton load
Strip in

L = Left of the mill gauge position
R = Right of the mill gauge position
W/R = Work roll

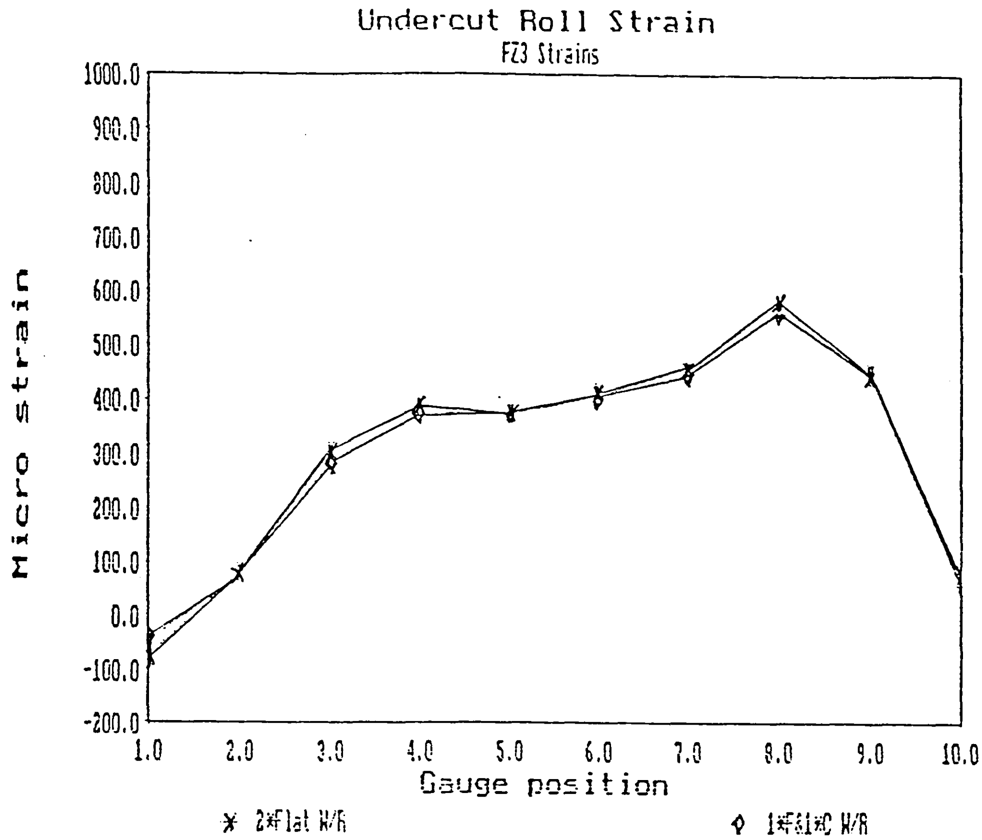
C



5" Taperd first intermediate rolls
1/2 Flat taper position
100 Ton load
No strip

W/R = Work roll
Top = Gauged roll in the top of the mill
Bott = Gauged roll in the bottom ofn the mill

d



5" Taperd first intermediate rolls
1/2 Flat taper positio.
Bottom mill position
100 Ton load
Strip in

W/R = Work rolls

Figure 32.
Strain Graphs Showing the Effects of Saddle Settings on Work Roll Strain.

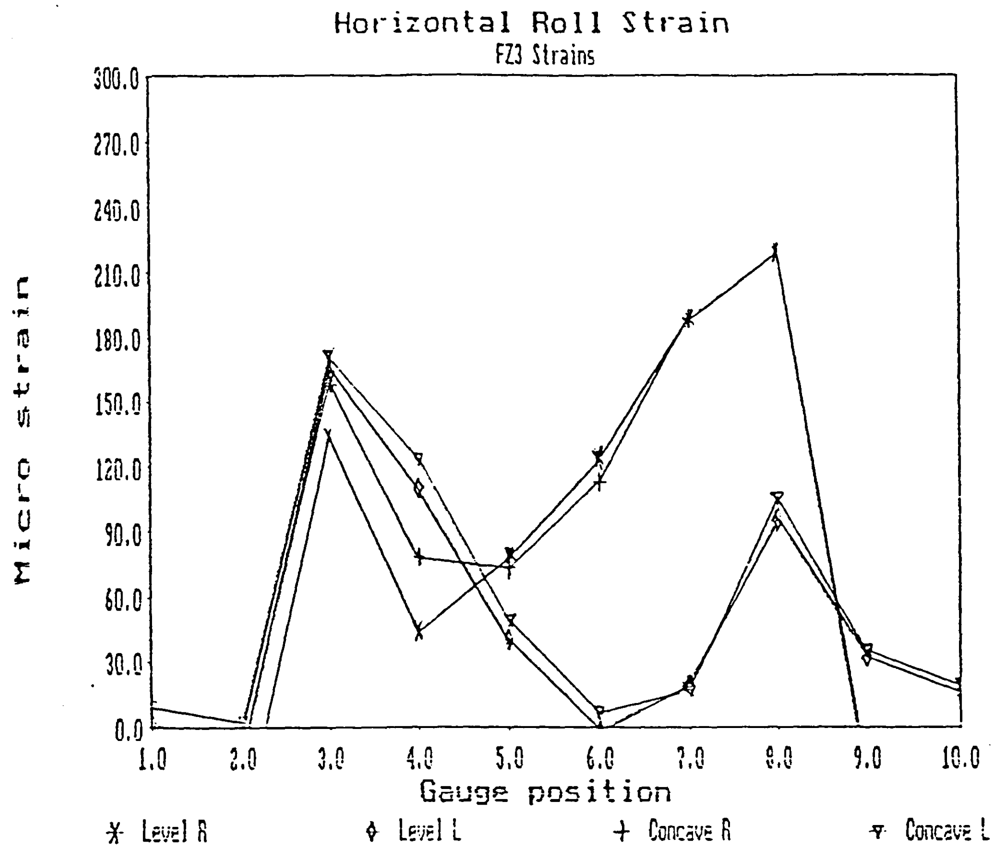
a) Horizontal Roll Strain.

b) Vertical Roll Strain.

c) Undercut Roll Strain.

a

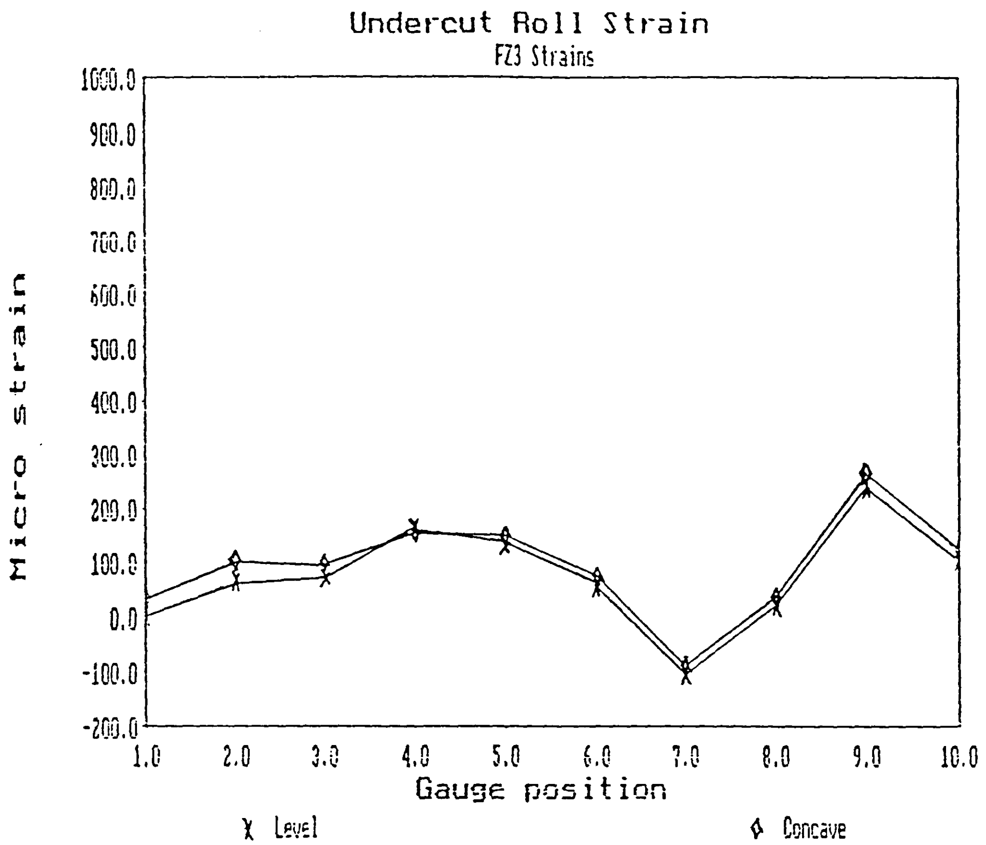
RESULTS SECTION 6 E ffects of saddle settings



7" Special taperd first intermediate rolls
1/2 Flat taper position
Two flat work rolls
Top mill position
100 Ton load
Strip in

Level = Saddle settings 5 5 5 5
Concave = Saddle settings 5 8 8 5
L = Left of the mill gauge positions
R = Right of the mill gauge positions

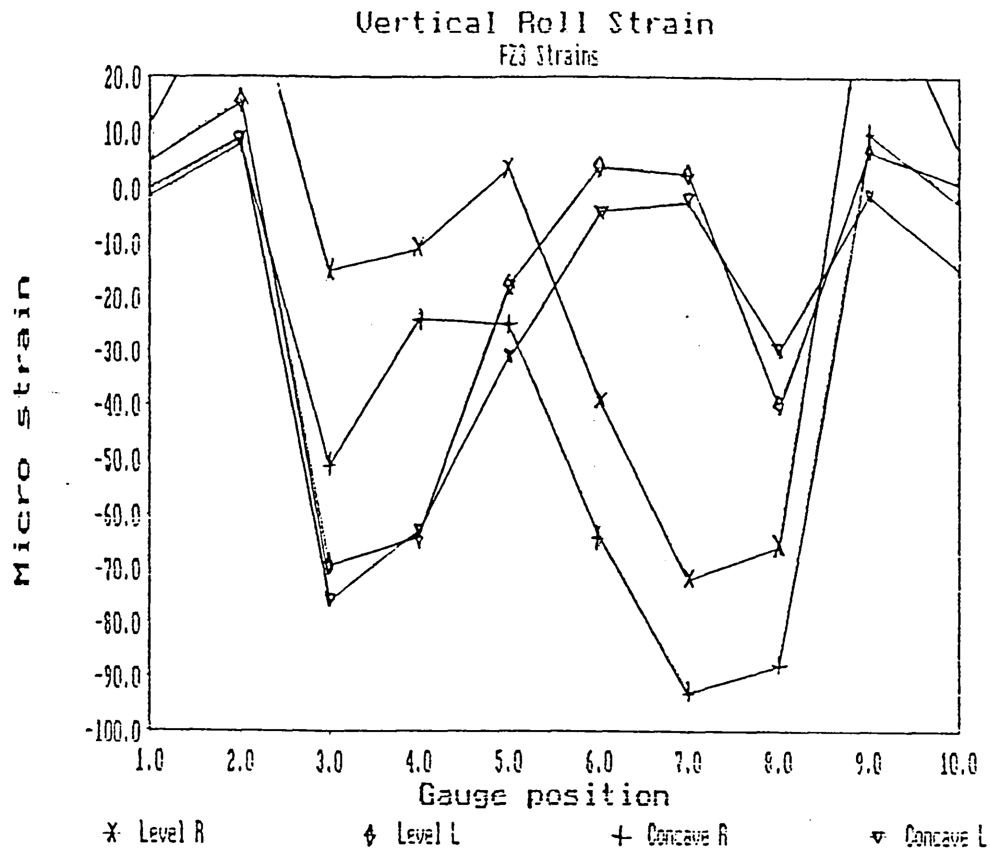
b



7" Special tapered first intermediate rolls
1/2 Flat taper position,
Two flat work rolls
Top mill position
100 Ton load
Strip in

Level = Saddle settings 5 5 5 5
Concave = Saddle settings 5 8 8 5
L = Left of the mill gauge positions
R = Right of the mill gauge positions

C



7" Special taperd first intermediate rolls
1/2 Flat taper position
Two flat work rolls
Top mill position
100 Ton Load
Strip in

Level Saddle settiggs 5 5 5 5
Concave = Saddle settings 5 .8 .8 5
L = Left of the mill gauge positions
R = Right of the mill gauge positions

Figure 33.
Strain Graphs Showing the Effects of Offset Castors on Work Roll Strain.

a) Horizontal Roll Strain.

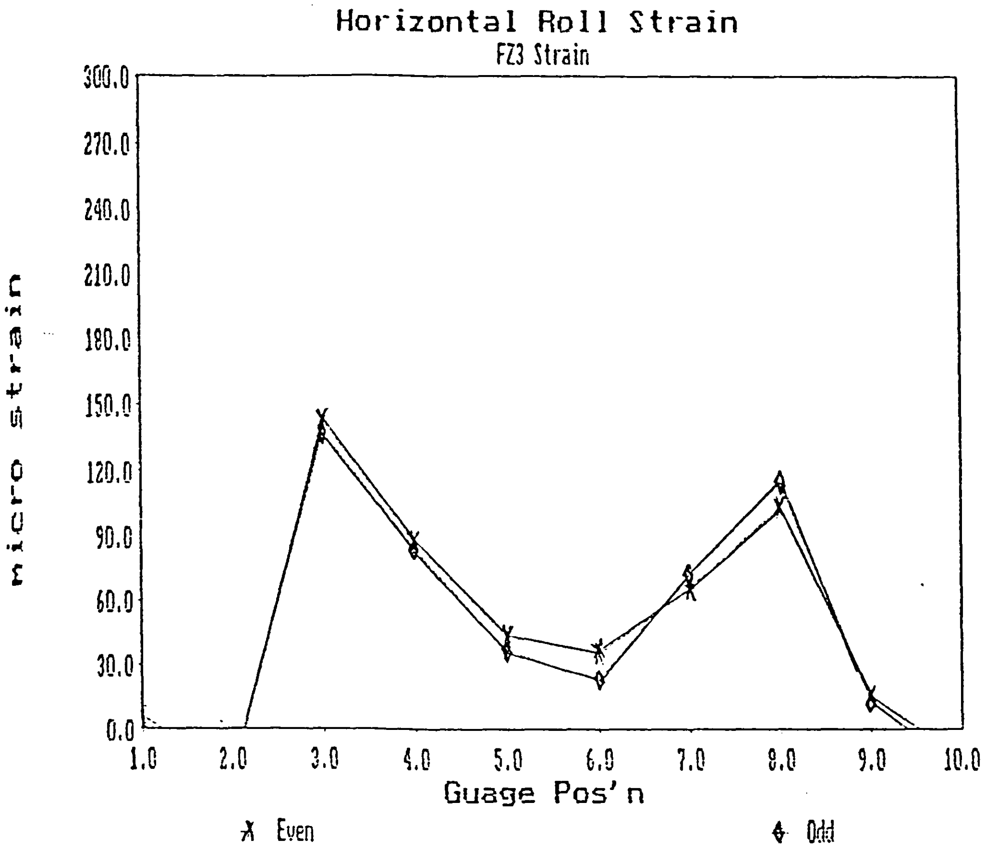
b) Horizontal Roll Strain.

c) Vertical Roll Strain.

d) Vertical Roll Strain.

a

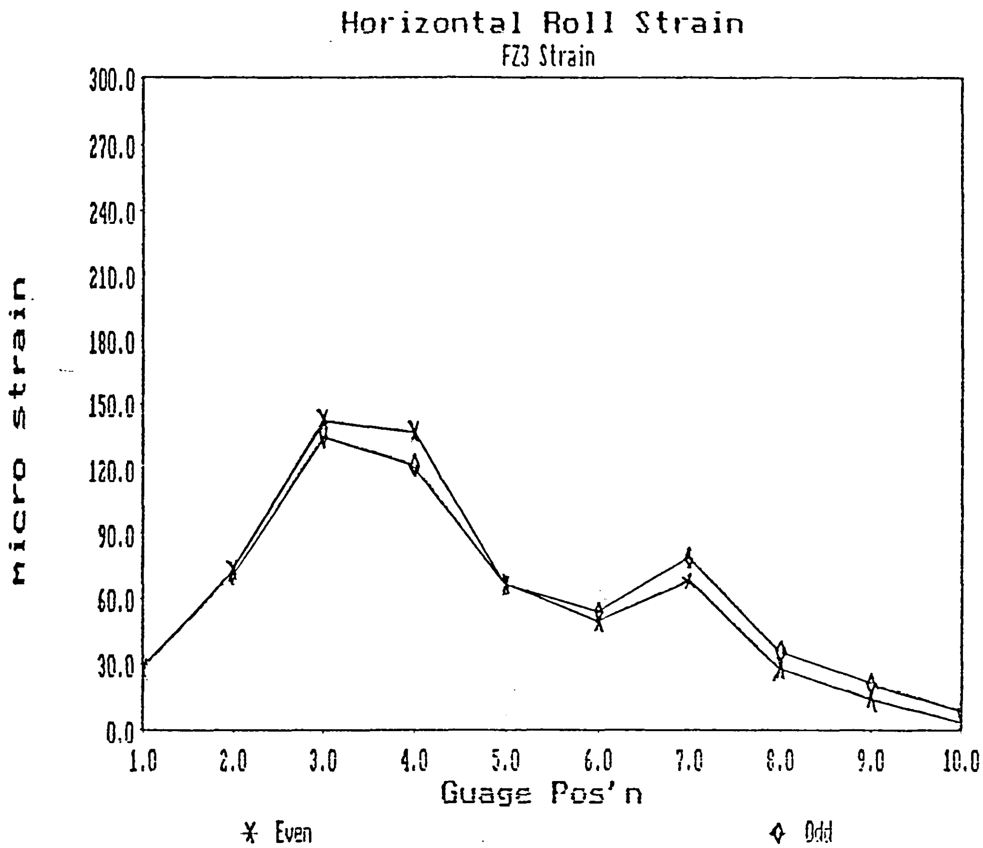
Effects of offsetting casters



7" Taperd first intermeddite rolls
Full flat taper position
Two flat work rolls
Top mill position
100 Ton load
Strip in

Even = Castor settings levl
Odd = Gasror settings 3 units difference

b



7" Taperd first intermediate rolls
1/2 flat taper position
Two flat work rolls
Top mill position
100 Ton load
Strip in

Even = Castor settings level
Odd Castor settings 3 units difference

Figure 34.
Strain Graphs Showing the Effects of Flat Ground First Intermediate Rolls on Work Roll Strain.

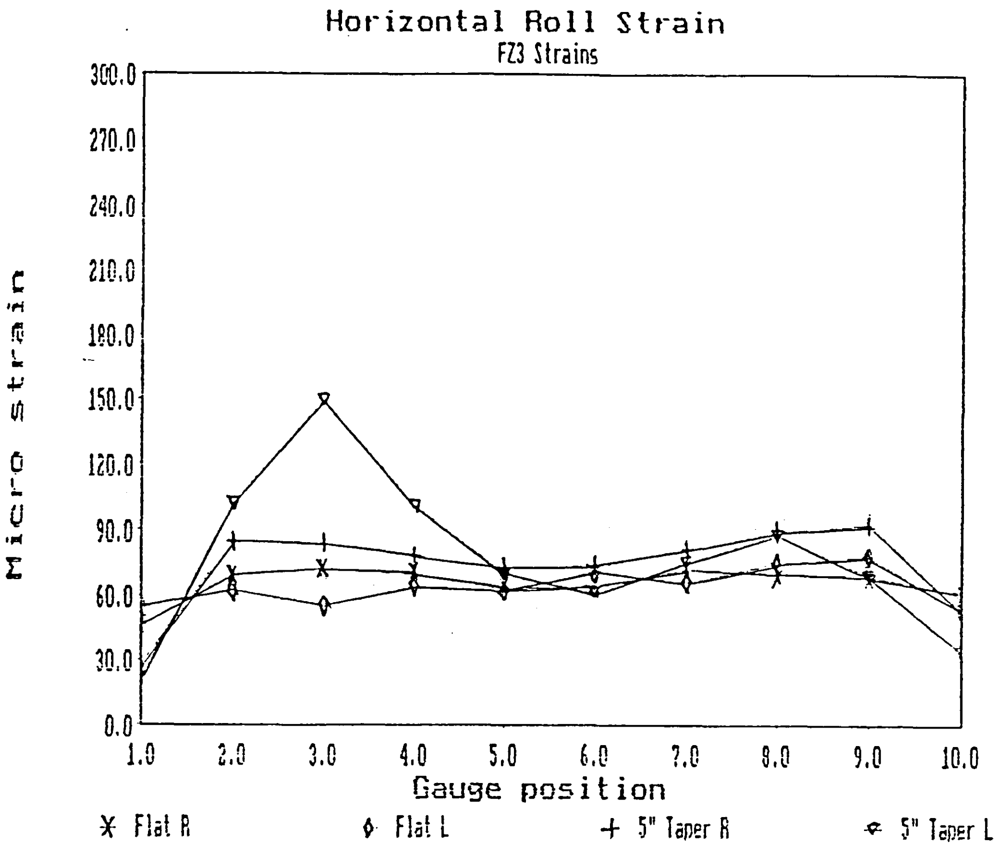
a) Horizontal Roll Strain.

b) Vertical Roll Strain.

c) Undercut Roll Strain.

a

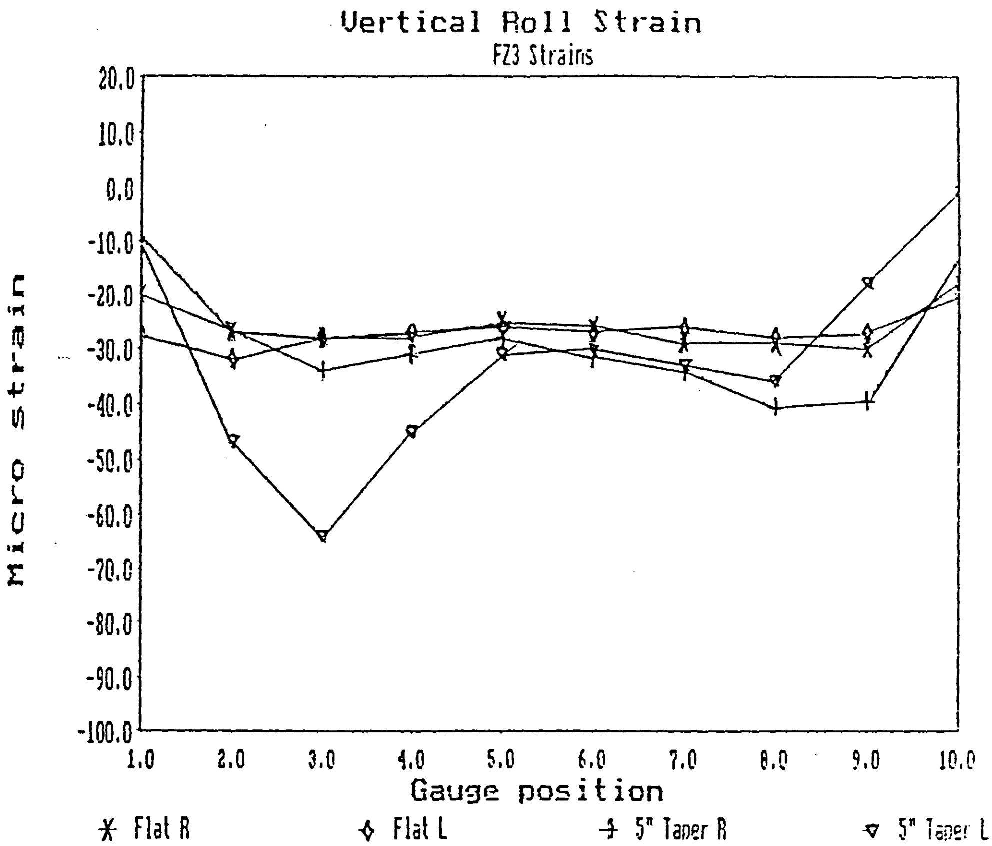
Effects of flat ground first intermediate rolls



1/2 Flat taper position
Two flat work rolls
Top mill position
100 Ton load
No strip

Flat = First intermediate roll with no taper
5" Taper = Taperd first intermediate roll
R = Right of the mill gauge positions
L = Left of the mill gauge positions

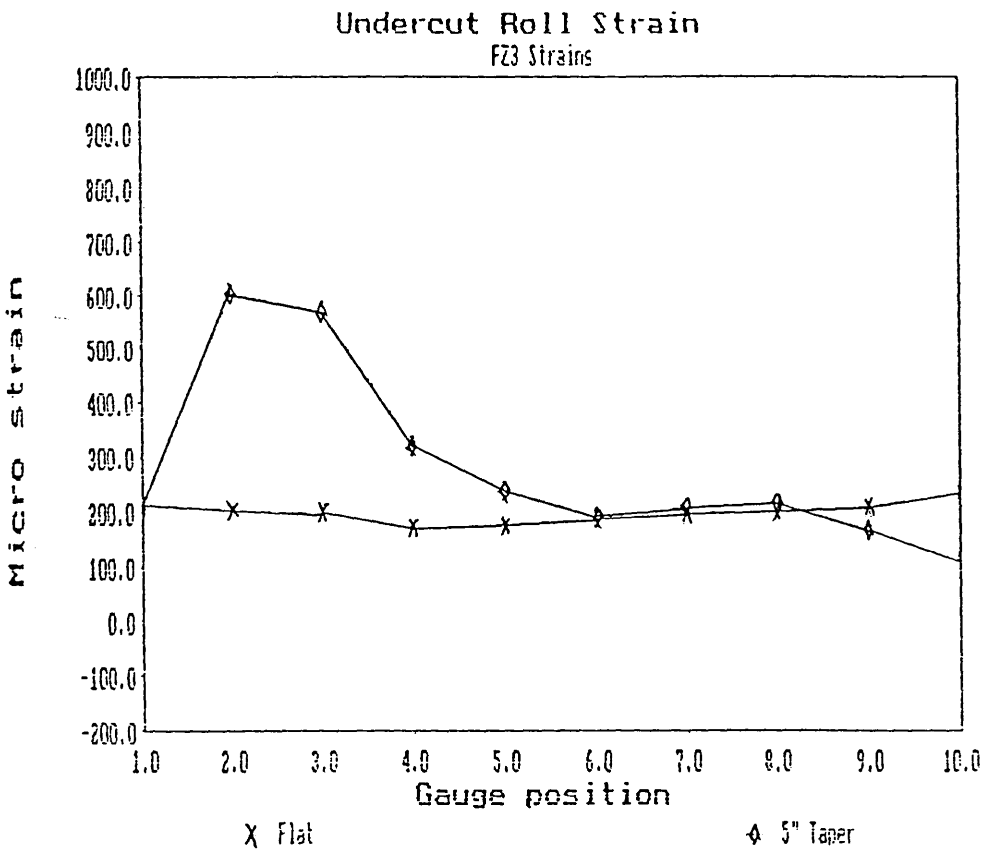
b



1/2 Flat taper position
Two flat work rolls
Top mill position
100 Ton load
No strip

Flat = First intermediate roll with no taper
5" Taper = Taperd first intermediate roll
R = Right of the mill gauge position
L = Left of mthe mill gauge position

C



7" Taperd first intermediate rolls
Two flat work rolls
Top mill position
100 To load
No strip

Flat = First intermediate rolls with no taper
5" Taper = Taperd first intermediate rolls

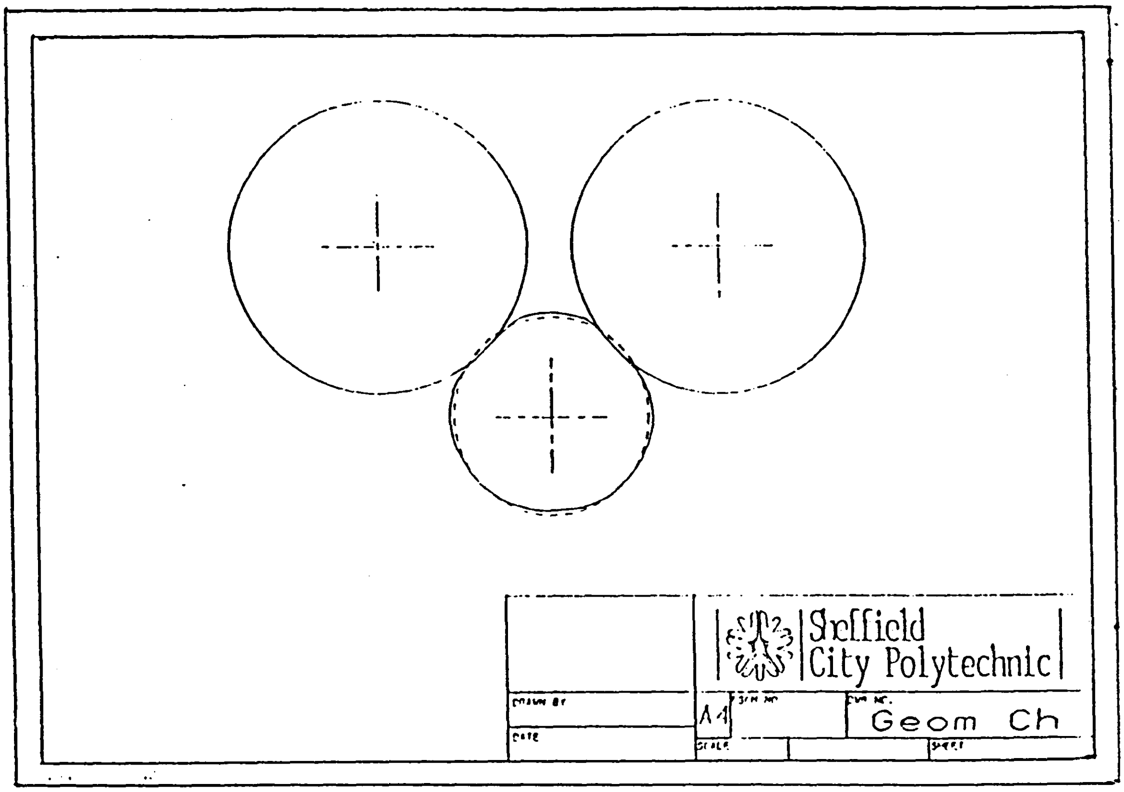
Figure 35.
Estimates of the way in which a Work Roll Changes Shape Under Load Based on Strain Results.

a) Cross Sectional Profile Changes.

b) Longitudinal Profile Changes.

Cross sectional profile change of a work roll under load

a



Longitudinal profile change of a work roll under load

b

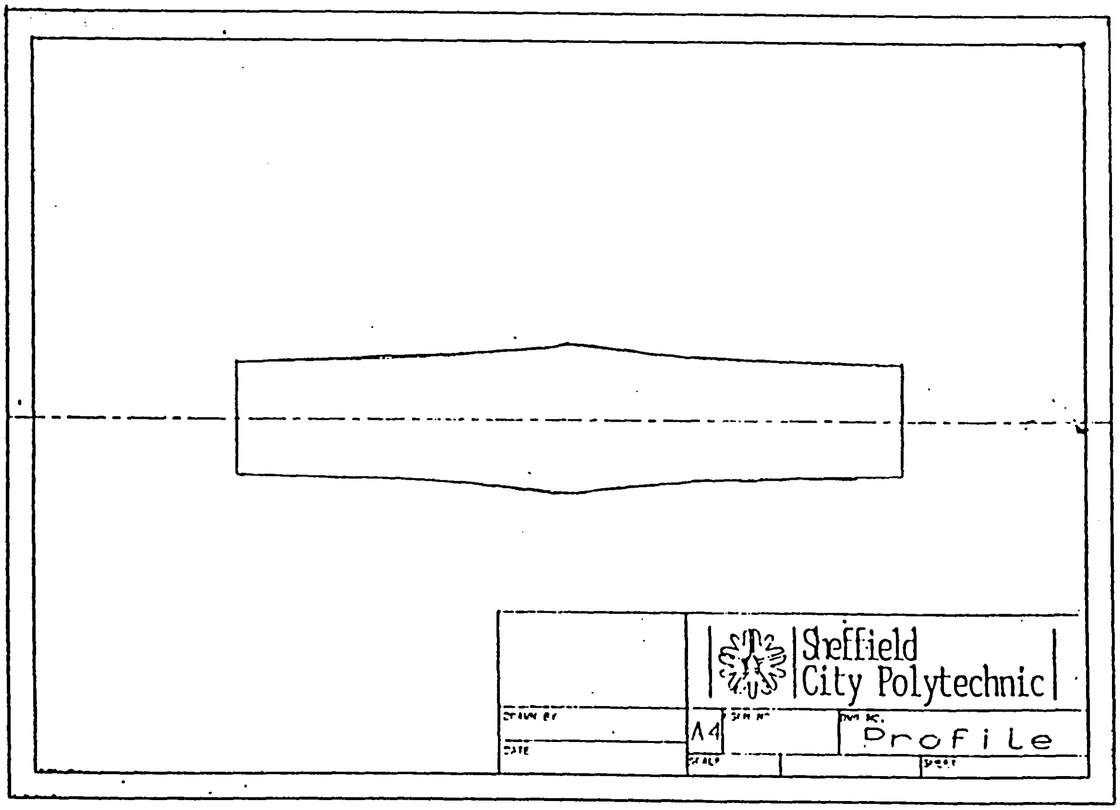
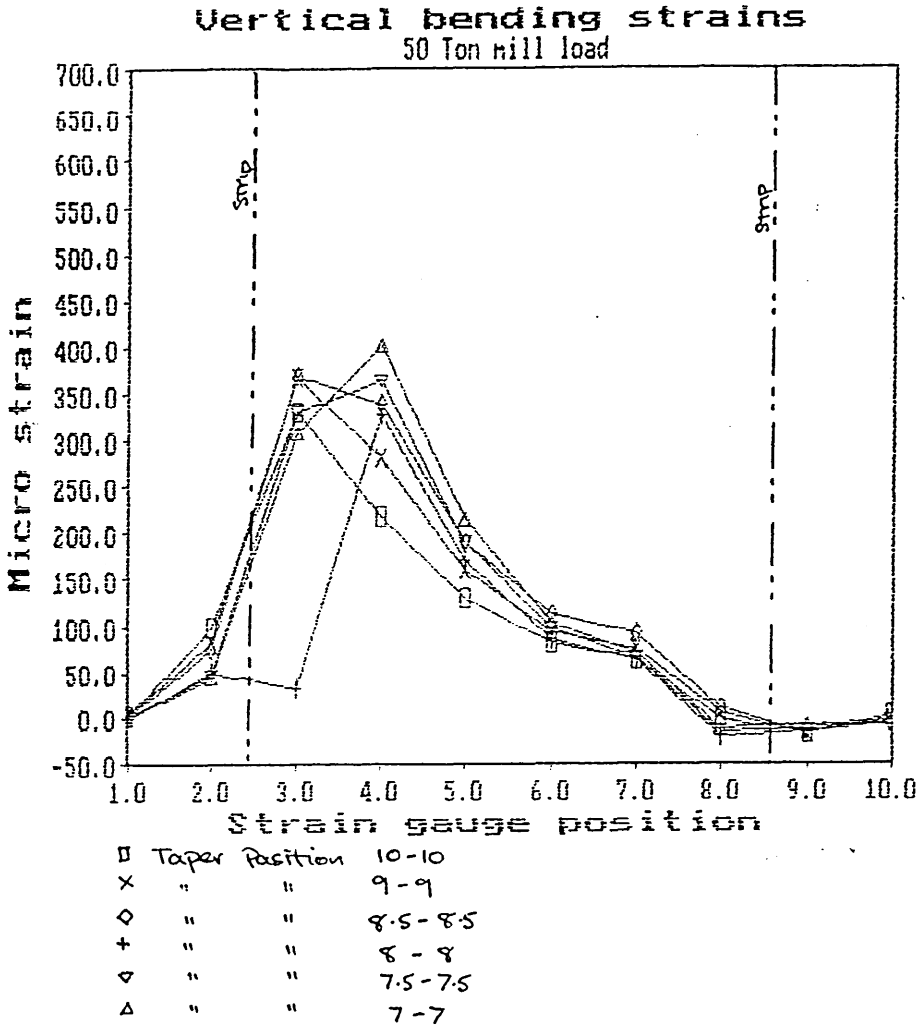


Figure 36.
Graphs of Vertical Work Roll Bending Strains Using 50T Mill Load and Different First Intermediate Roll Positions.

Vertical roll bending strains with different first intermediate roll positions.



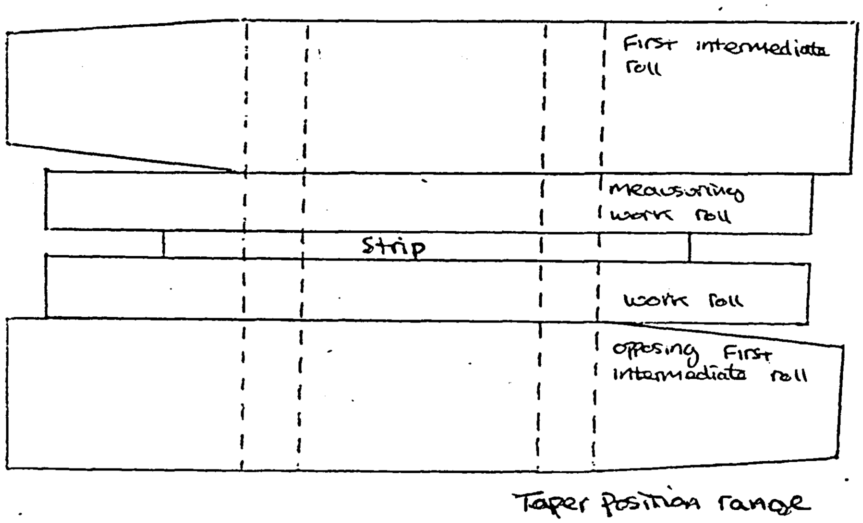
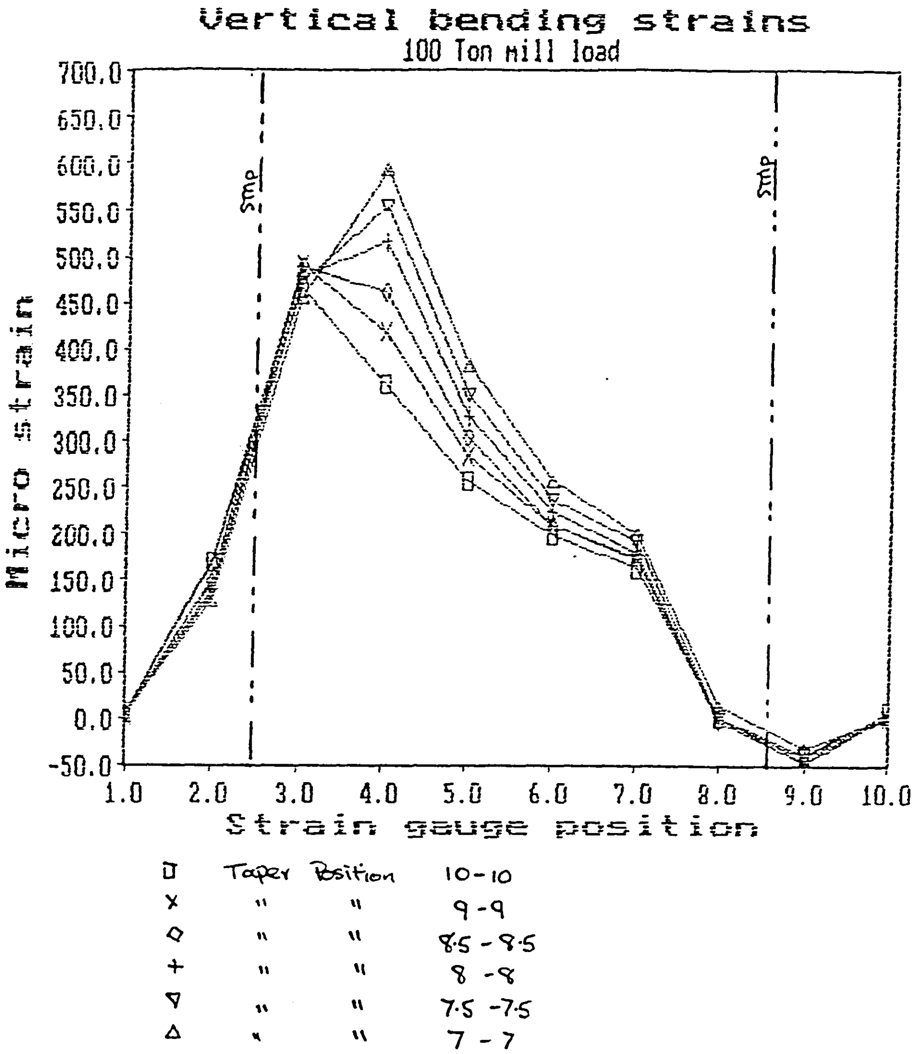


Figure 37.
Graphs of Vertical Work Roll Bending Strains Using 100T Mill Load and Different First Intermediate Roll Positions.

First intermediate roll positions



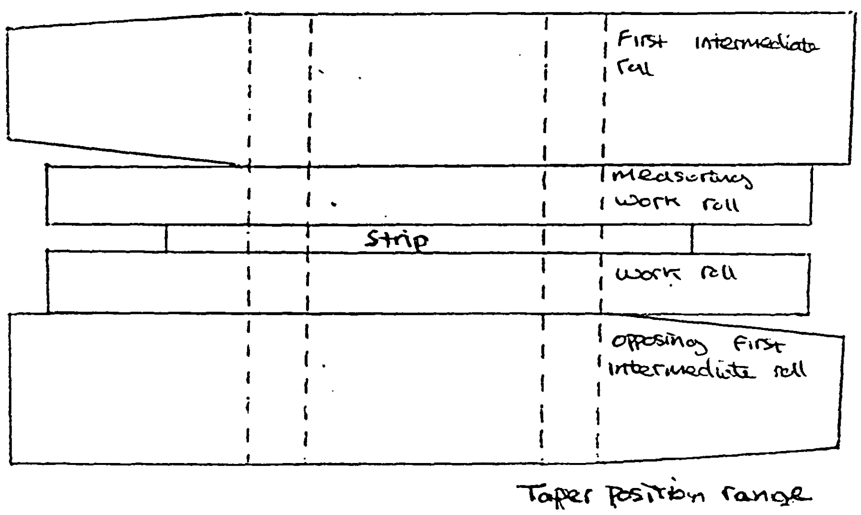
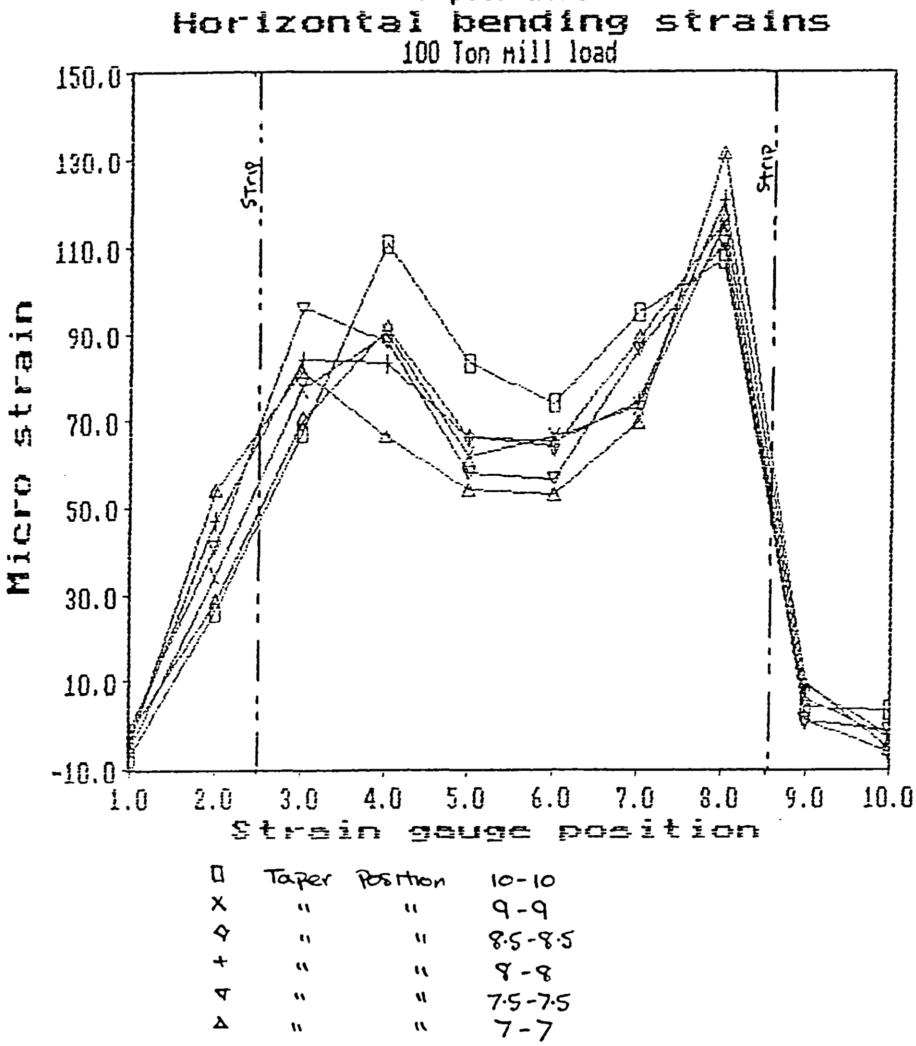


Figure 38.
Graphs of Horizontal Work Roll Bending Strains Using 100T Mill Load and Different First Intermediate Roll Positions.

Horizontal roll bending strains with different first intermediate roll positions



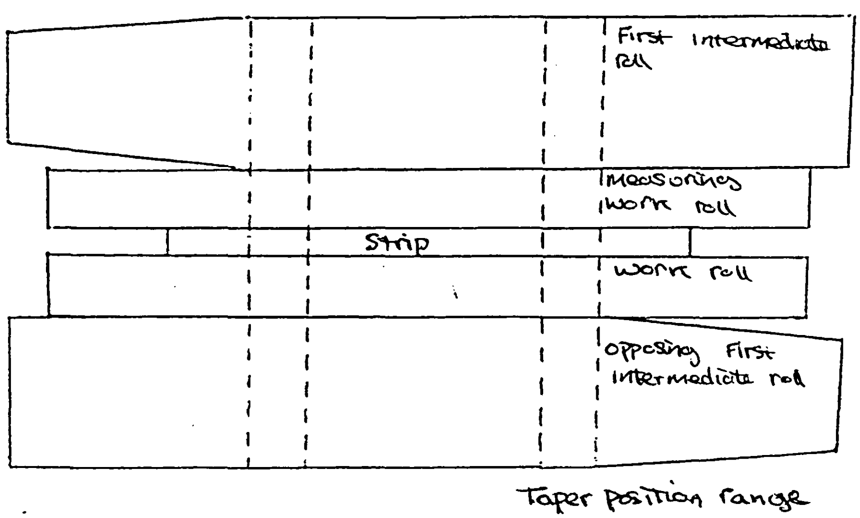


Figure 39.

Estimates of the Roll Gap Profile
With Associated Strip Shape Defects
Based on Work Roll Strain Results.

Sequences of Strip Shape Defects.

Strip shape history

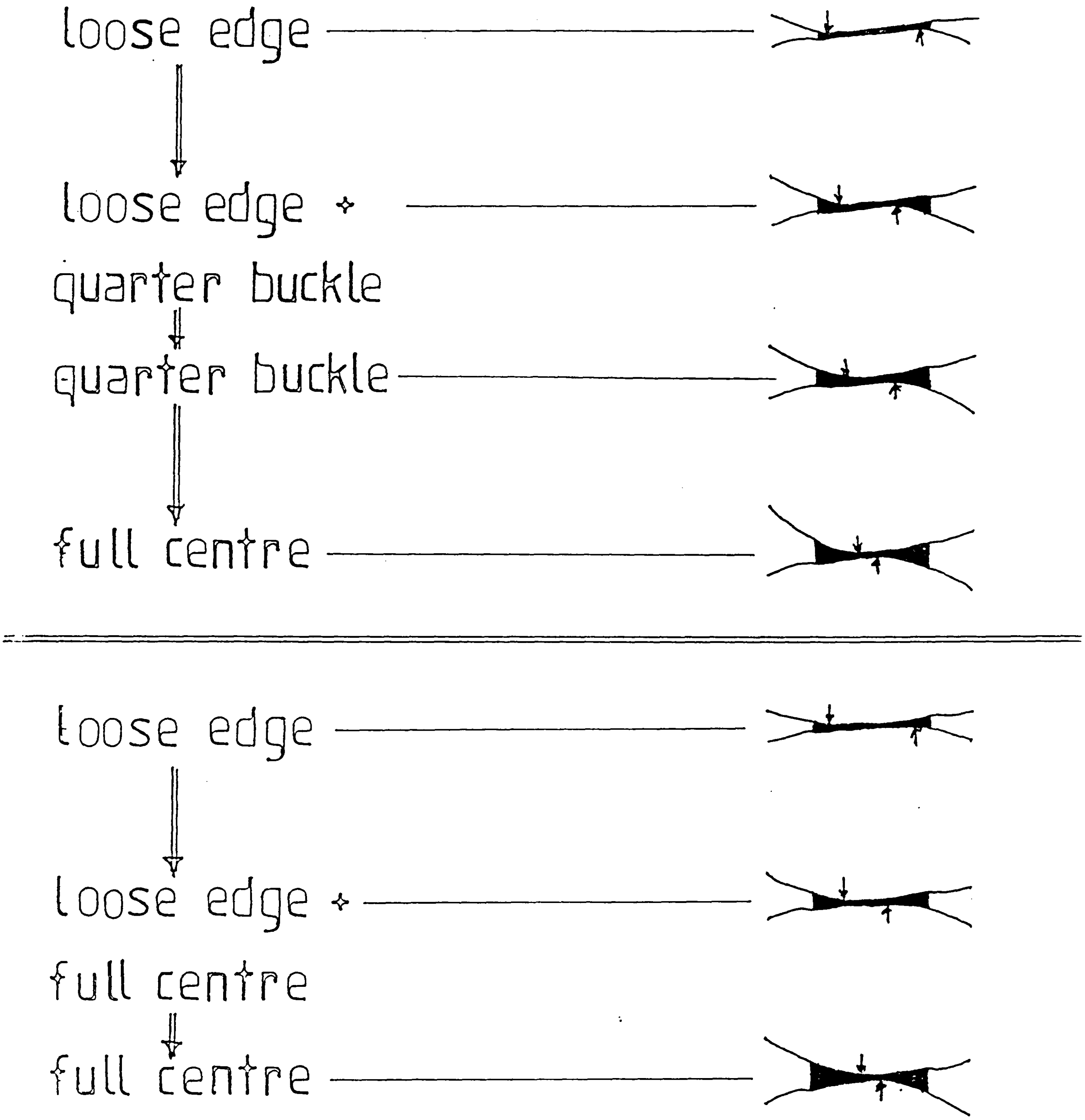
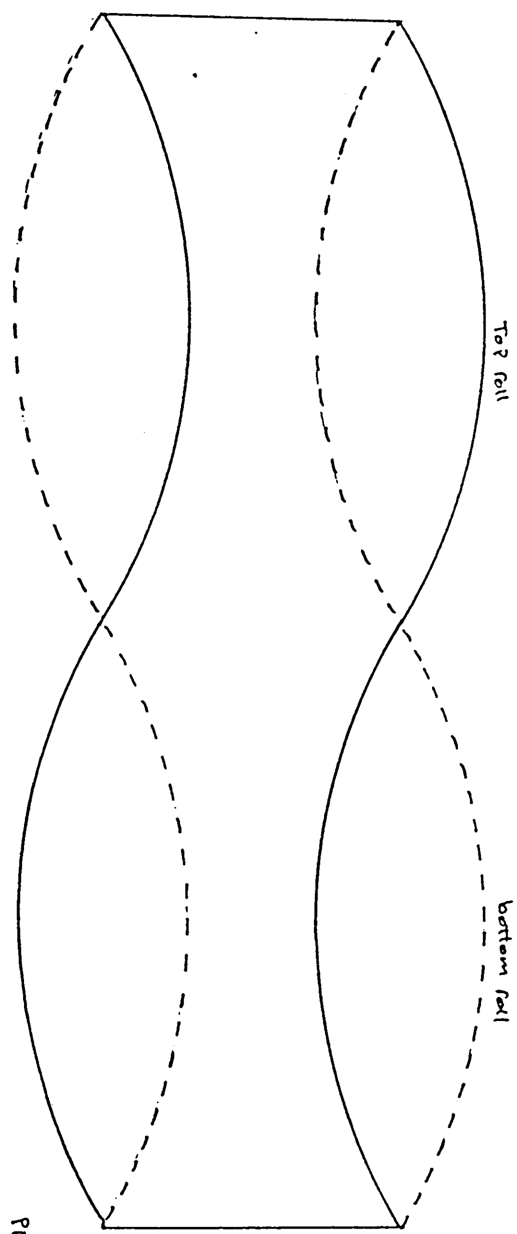


Figure 40.
Horizontal "S" Bending of the Loaded Work Rolls Based on Work Roll Strain Results.

Exagerated view of work roll bending



Plan view of exagerated work roll bending

Figure 41.
Different First Intermediate Roll Profiles Used to Improve Strip Shape.

a) Ordinary Profile

b) Double Tapered Profile

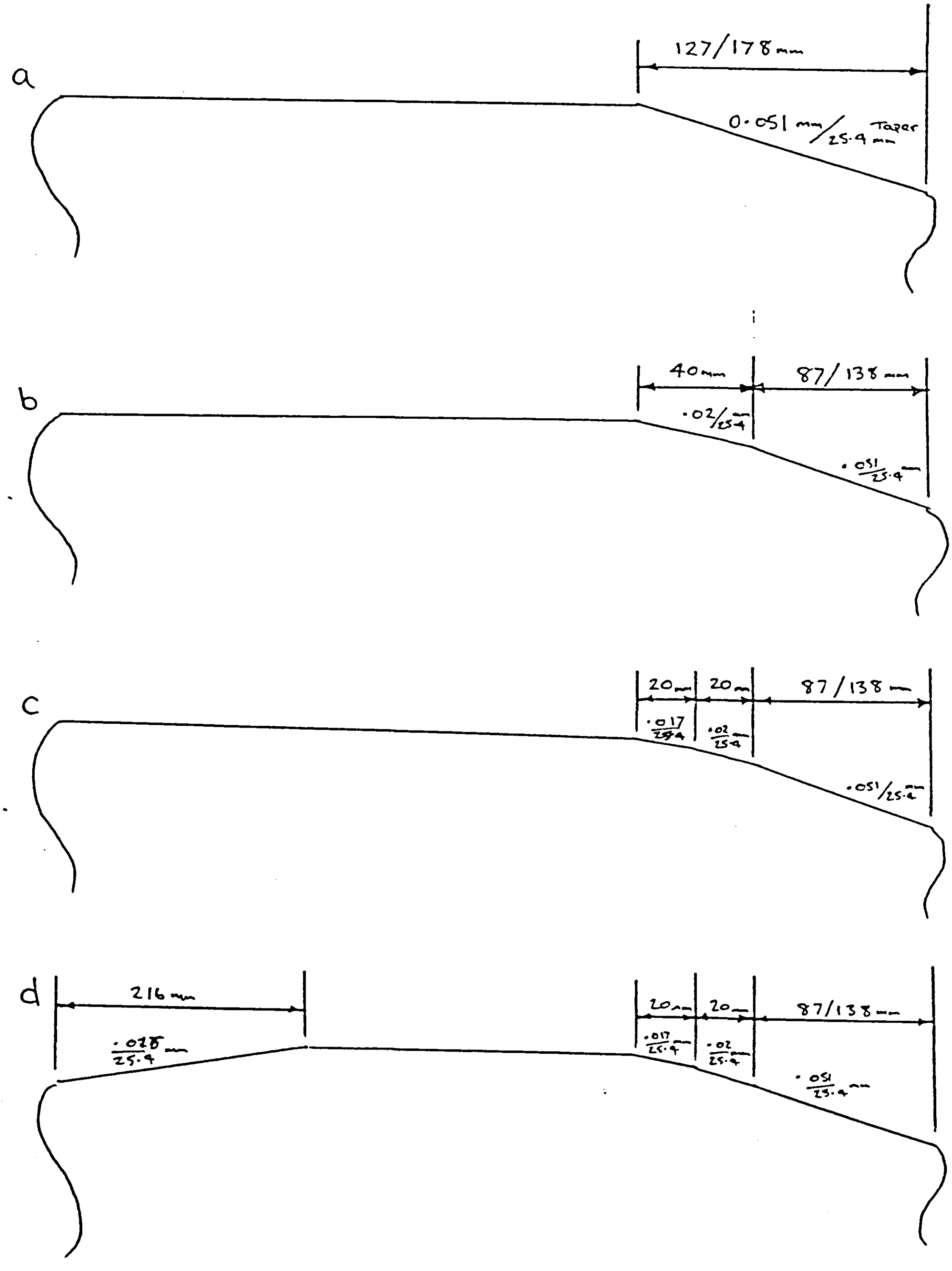
c) Triple Taper With Back Taper

d) Triple Taper With Back Taper

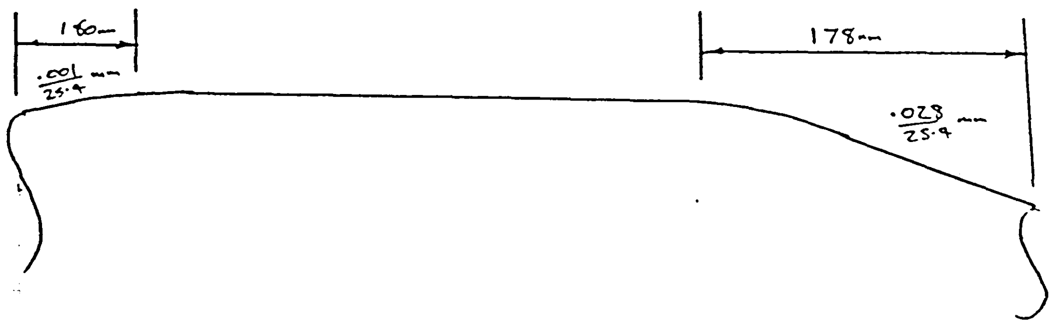
e1) Blended Taper

e2) Blended Taper With Back Taper

f) Complex Profile


a
127/178 mm
0.051 mm/25.4 mm Taper
b
40 mm
87/138 mm
.02/25.4 mm
.051/25.4 mm
c
20 mm
20 mm
87/138 mm
.017/25.4
.02/25.4 mm
.051/25.4 mm
d
216 mm
20 mm
20 mm
87/138 mm
.017/25.4 mm
.02/25.4 mm
.051/25.4 mm

ei


160mm
.001/25.4 mm
178mm
.028/25.4 mm

eii


120mm
.001/25.4 mm
127mm
.022/25.4 mm

f

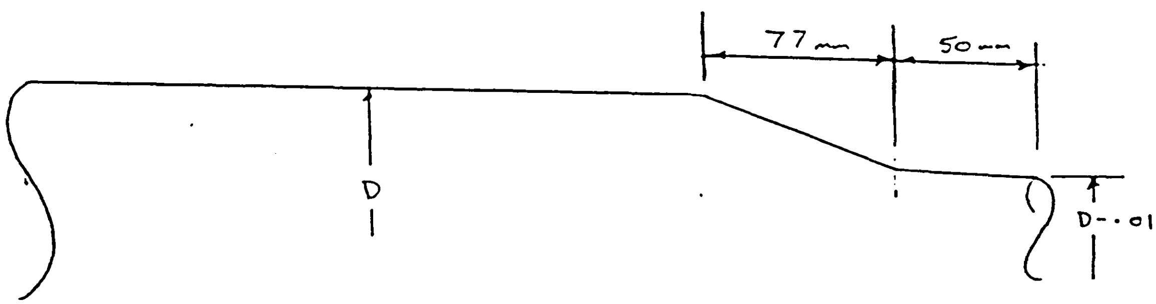
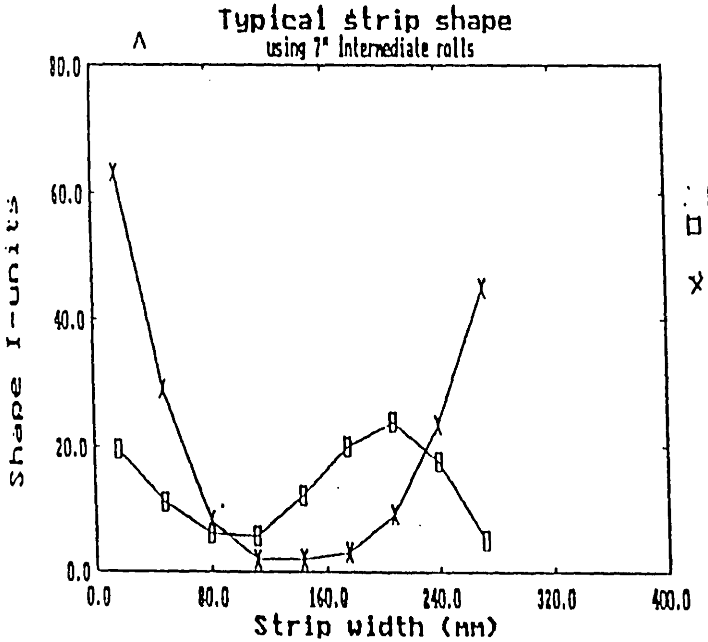

77mm
50mm
D
D - .01

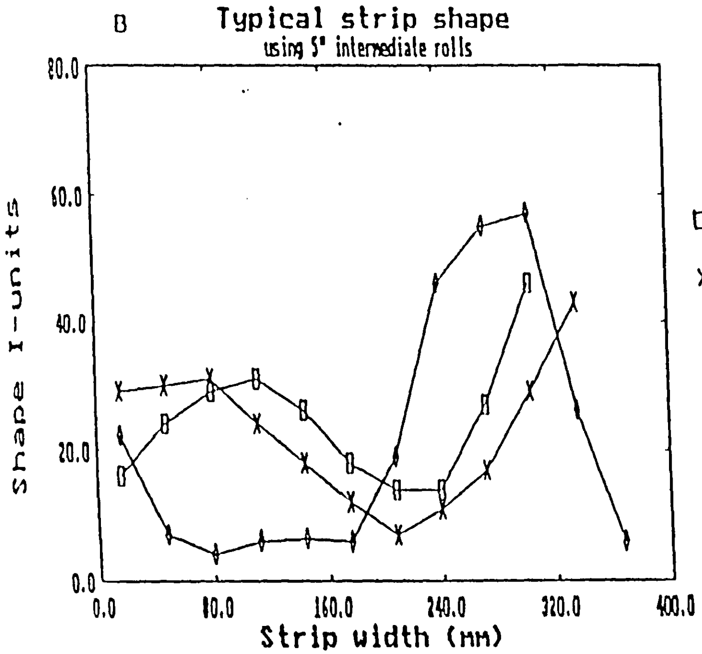
Figure 42.
Graphs Showing Examples of Typical Strip Shape Rolled Using Ordinary Tapered First Intermediate Rolls.

A



	Folio No	Mat'l	Width	Gauge	Reduction
□	11891/11	301	305mm	.2mm	62%
X	11891/11	301	305mm	.2mm	62%

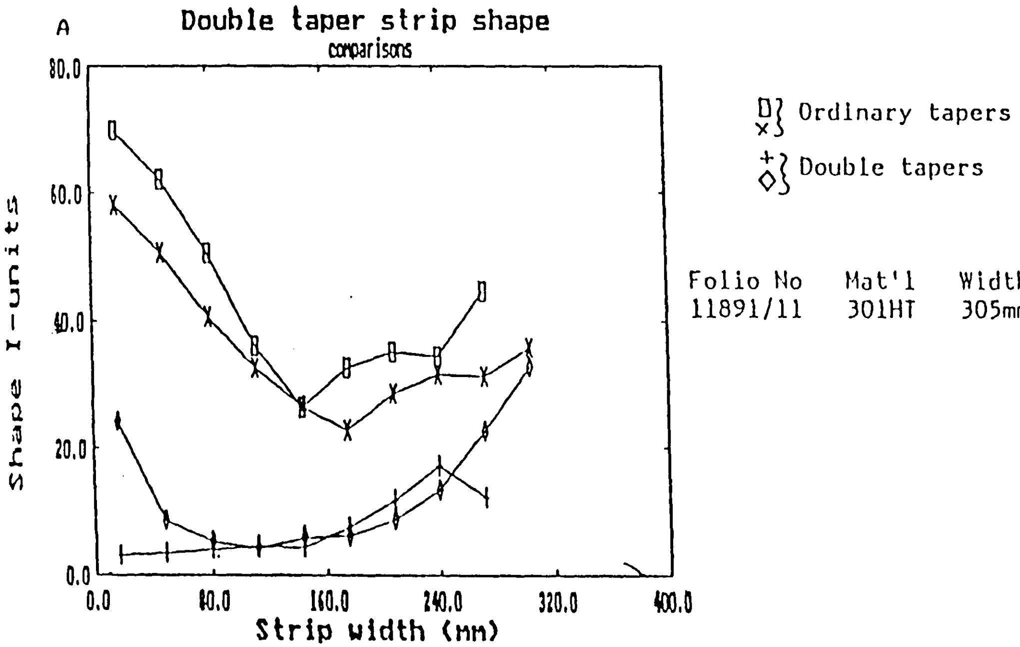
B



	Folio No	Mat'l	Width	Gauge	Reduction
□	12405/11	301	390mm	.215mm	77%
X	12405/11	301	390mm	.215mm	77%
◊	14715/11	301UC	395mm	.215mm	77%

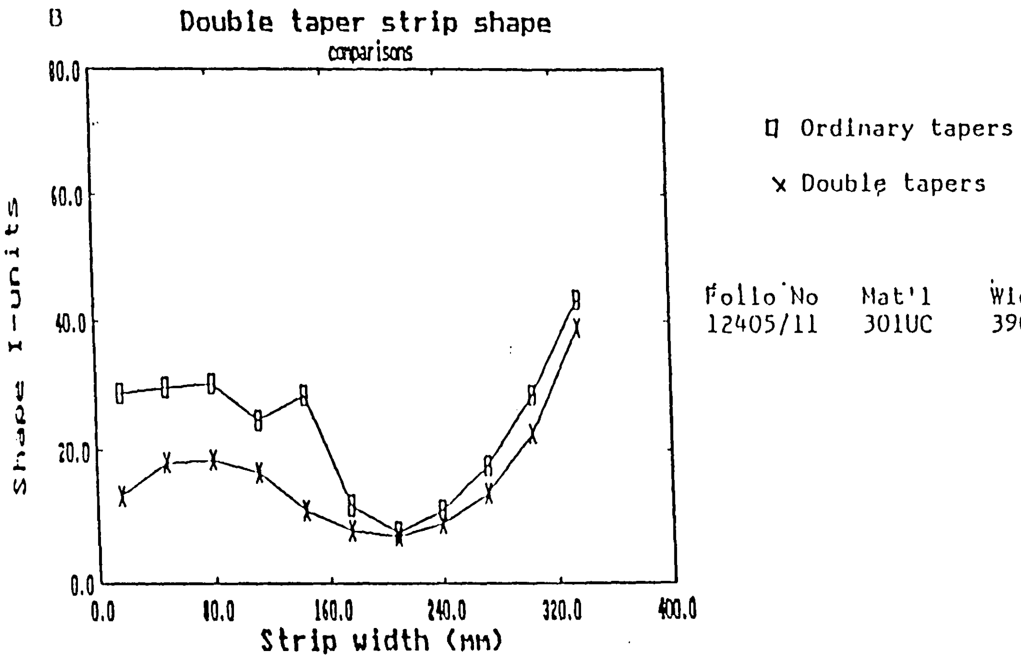
Figure 43.
Graphs Showing Examples of Strip Shape Rolled Using Double Tapered First Intermediate Rolls.

A



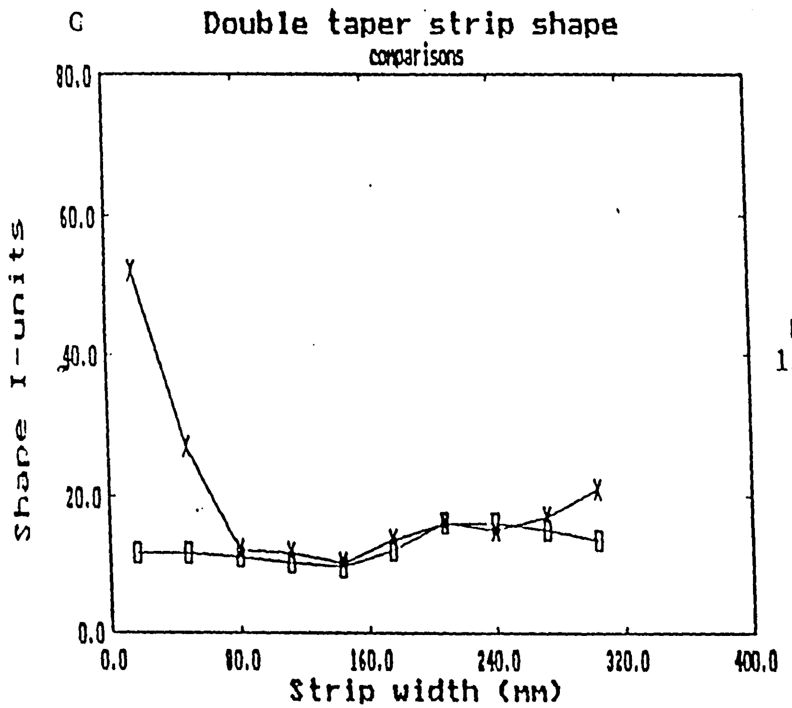
Folio No	Mat'l	Width	Gauge	Reduction
11891/11	301HT	305mm	.203mm	62%

B



Folio No	Mat'l	Width	Gauge	Reduction
12405/11	301UC	390mm	.215mm	77%

G



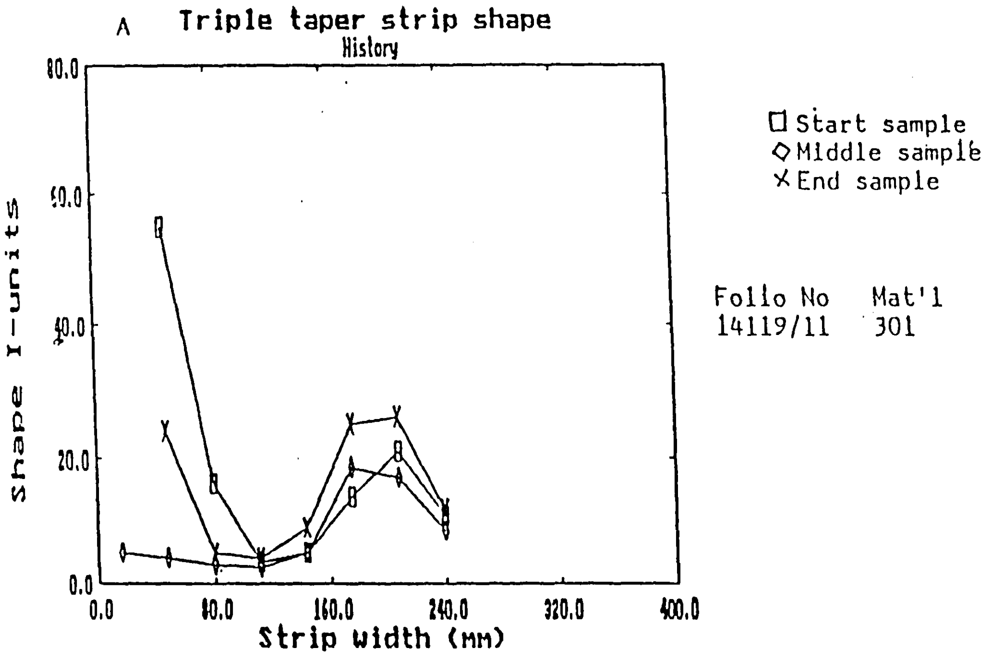
□ Ordinary tapers

X Double tapers

Folio No	Mat'l	Width	Gauge	Reduction
12773/11	301HT	323mm	.3mm	50%

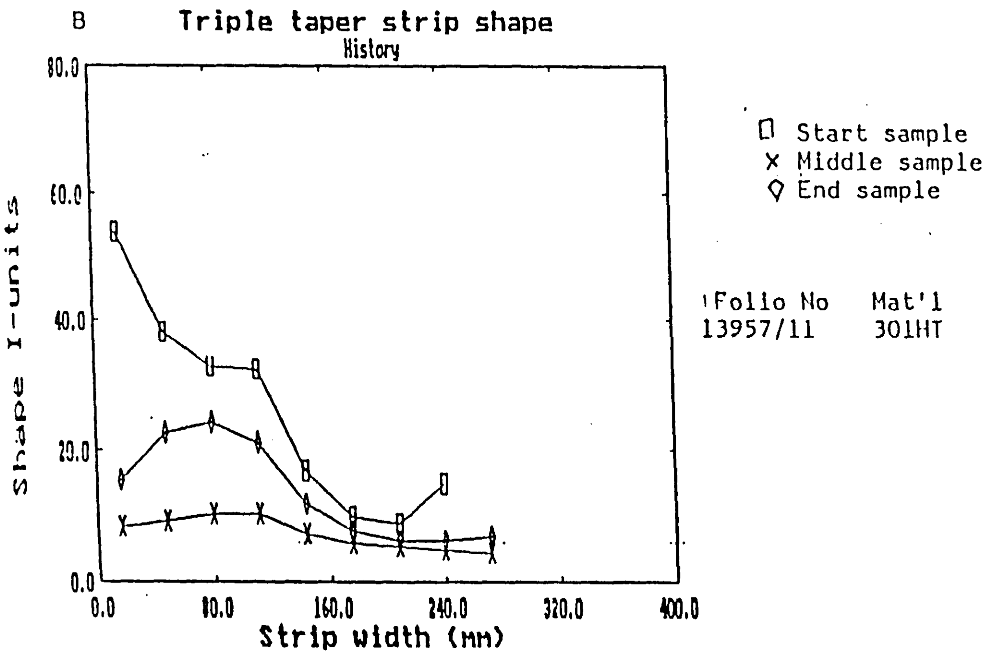
Figure 44.
Graphs Showing Examples of Strip Shape Rolled Using Triple Tapered First Intermediate Rolls.

A



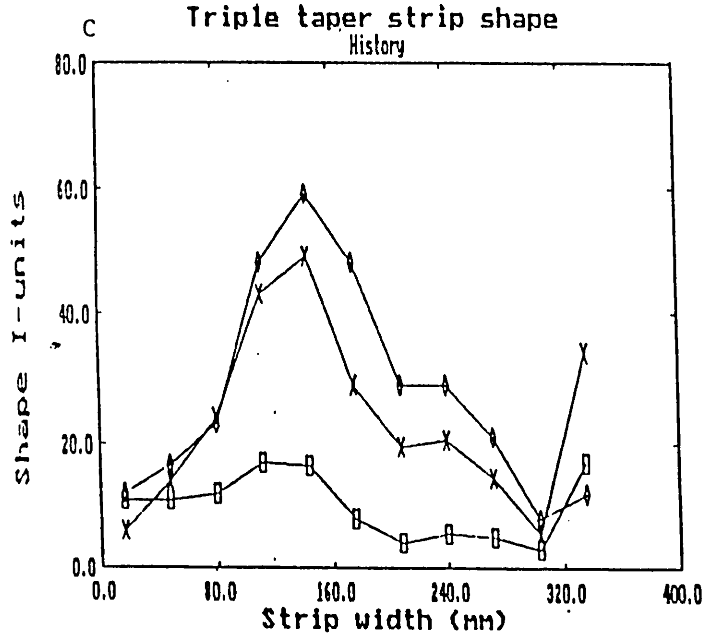
Folio No	Mat'l	Width	Gauge	Reduction
14119/11	301	255mm	.2mm	56%

B



Folio No	Mat'l	Width	Gauge	Reduction
13957/11	301HT	314mm	.4mm	79%

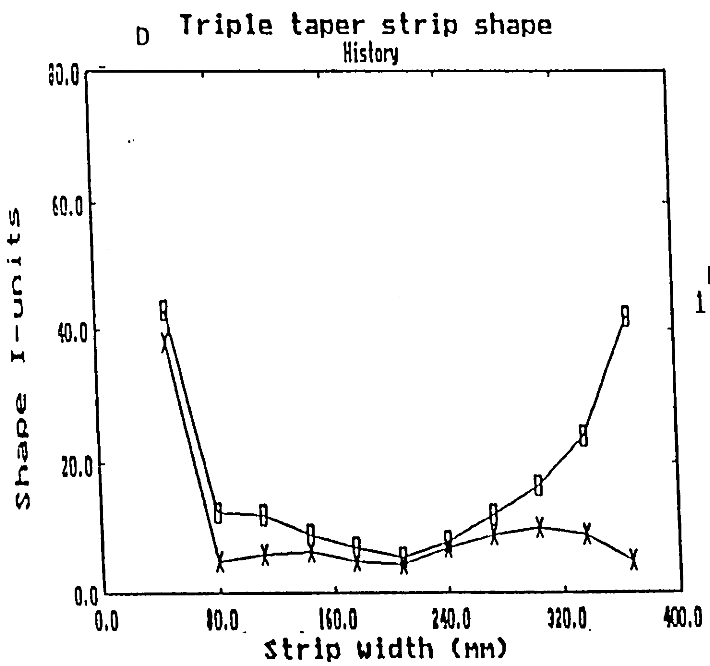
C



□ Start sample
X Middle sample
◇ End sample

Folio No	Mat'l	Width	Gauge	Reduction
14119/11	301HT	388mm	.2mm	58%

D

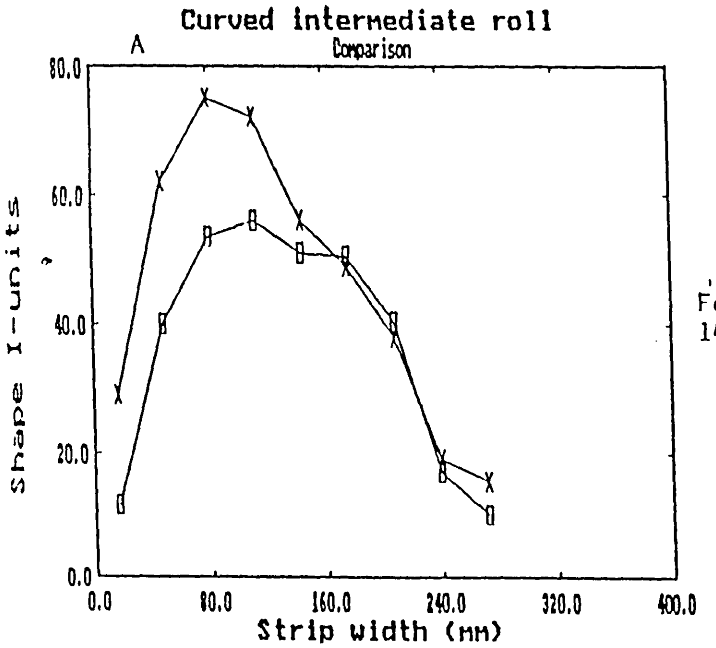


□ Start sample
X End sample

Folio No	Mat'l	Width	Gauge	Reduction
13327/11	304	388mm	.2mm	69%

Figure 45.
Graphs Showing Examples of Strip Shape Rolled Using Curved Tapered First Intermediate Rolls.

A

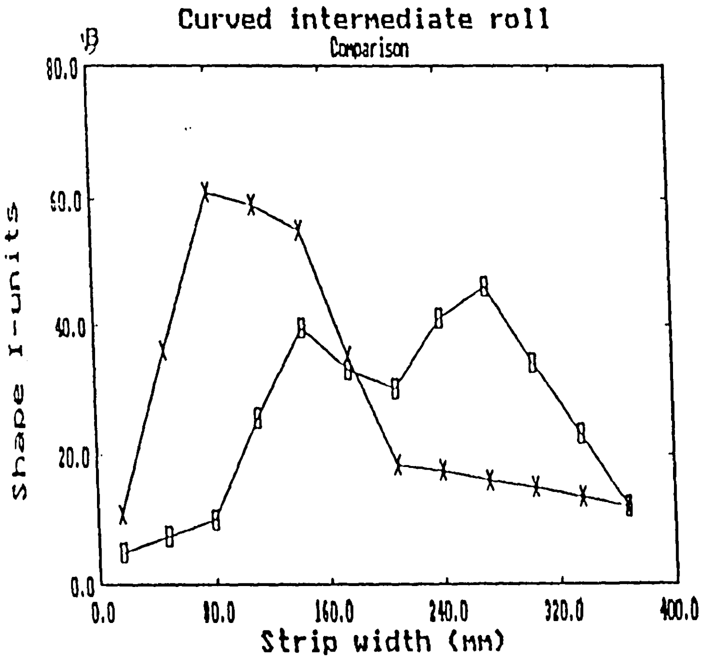


☐ Curved intermediate rolls

X Ordinary intermediate rolls

Folio No	Mat'l	Width	Gauge	Reduction
14415/11	316	312mm	.3mm	75%

B



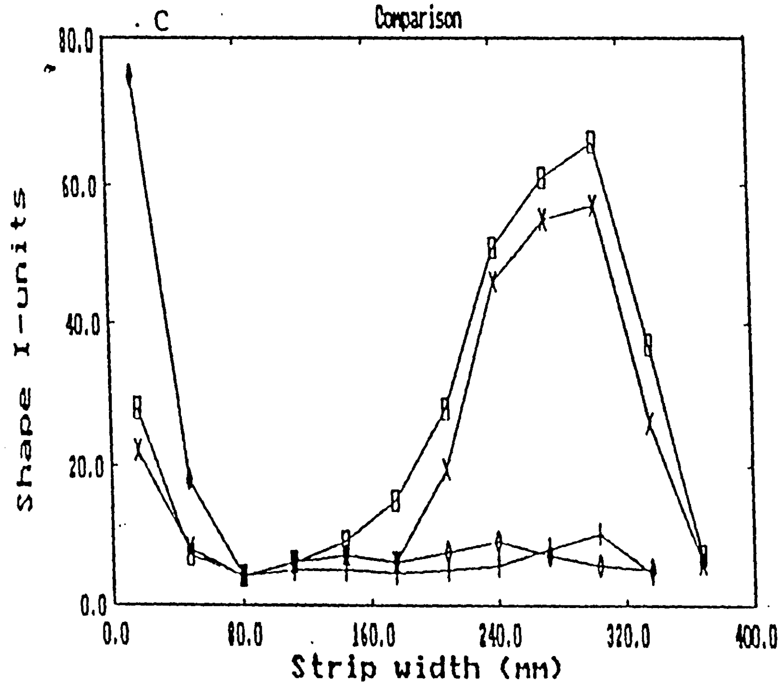
☐ Curved intermediate rolls

X Ordinary intermediate rolls

Folio No	Mat'l	Width	Gauge	Reduction
14259/11	301HT	416mm	.3mm	

Curved intermediate roll

Comparison

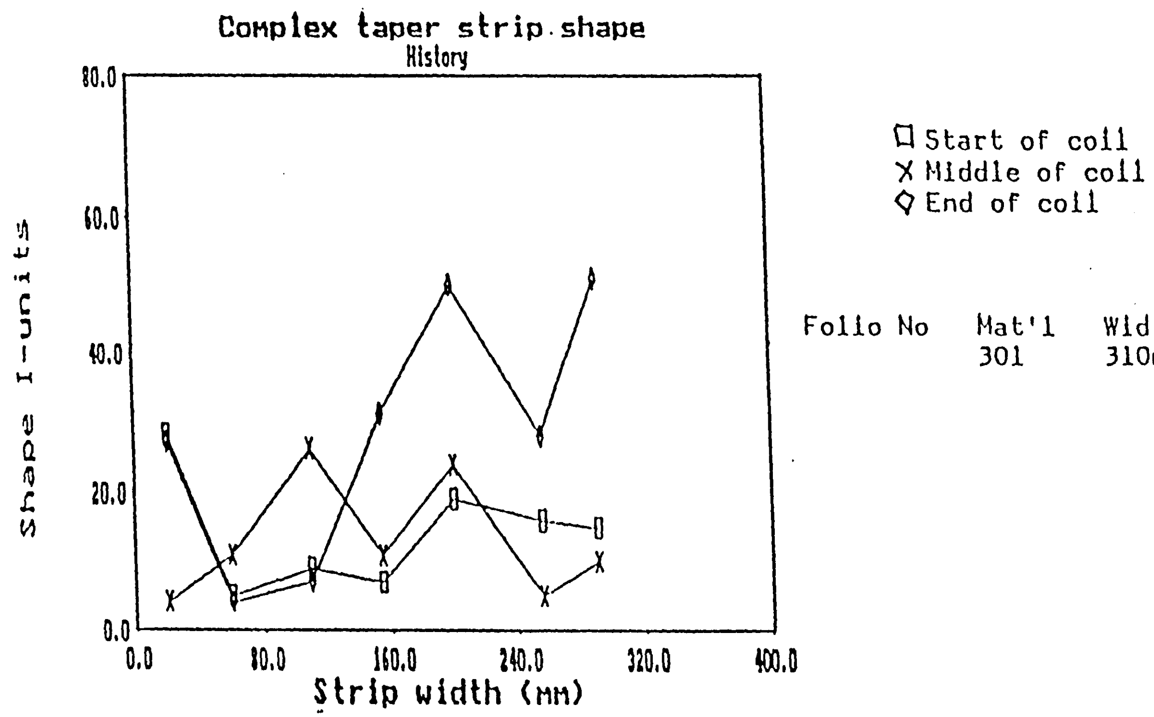


□ Start sample ordinary intermediate roll
× Middle sample " " "

+ Start sample curved " "
◇ Middle sample " " "

Folio No	Mat'l	Width	Gauge	Reduction
14715/11	301UC	394mm	.215mm	77%

Figure 46.
Graphs Showing Examples of Strip Shape Rolled Using Complex Tapered First Intermediate Rolls.



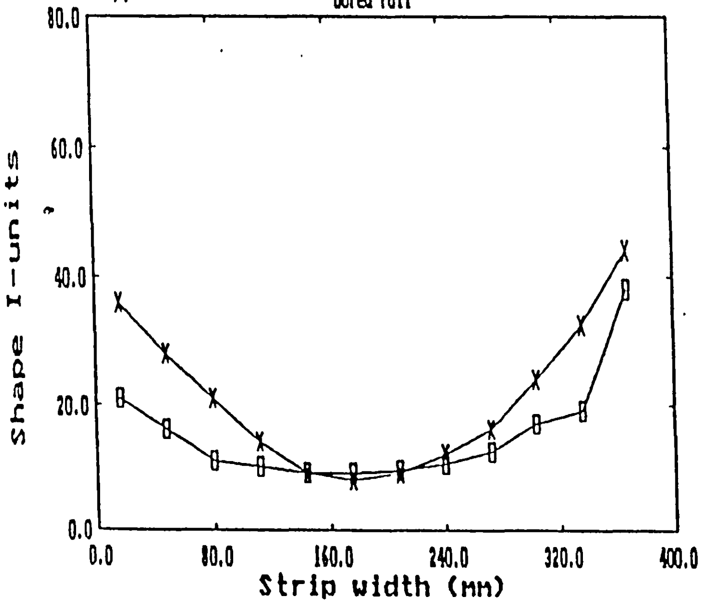
Folio No	Mat'l	Width	Gauge	Reduction
	301	310mm	.3mm	41%

Figure 47.
Graphs Showing Examples of Strip Shape Rolled Using Bored (hollow) Work Rolls.

A

Work roll strip shape trial

Bored roll



□ Solid Work rolls

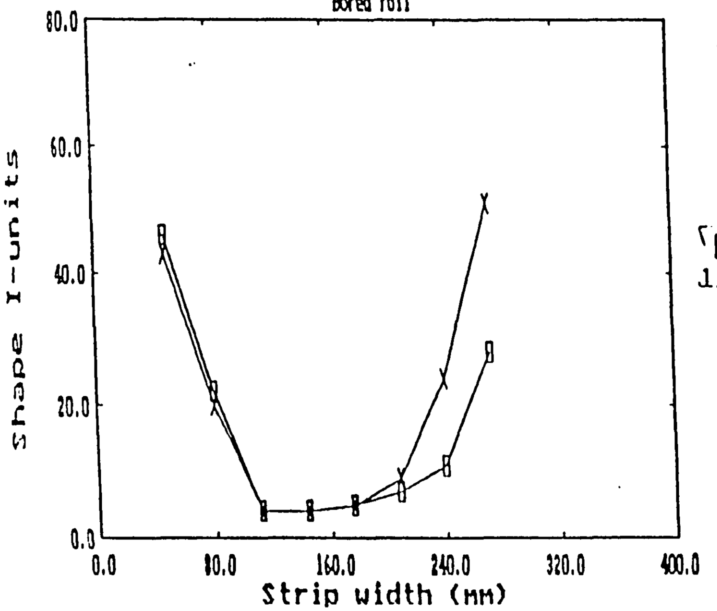
X Bored Work rolls

Folio No	Mat'l	Width	Gauge	Reduction
13175/11	301HT	406mm	.4mm	52%

B

Work roll strip shape trial

Bored roll

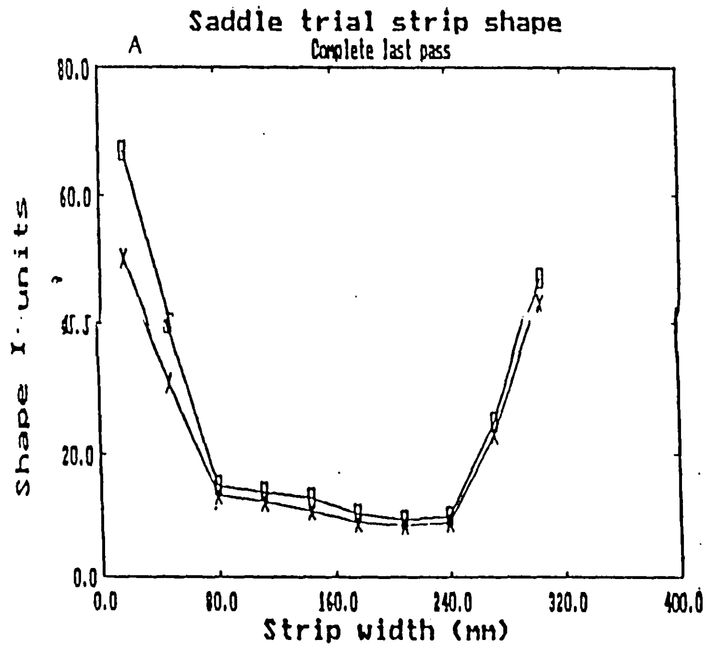


□ Solid Work rolls

X Bored Work rolls

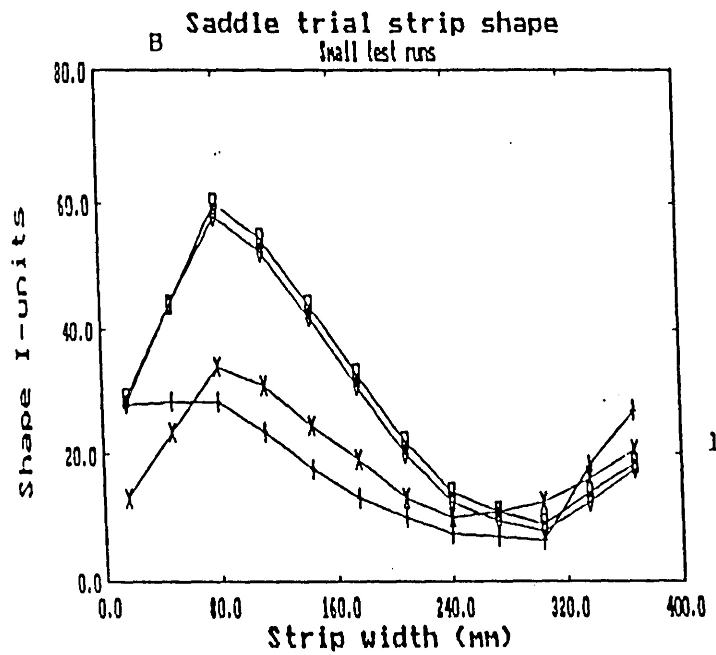
Folio No	Mat'l	Width	Gauge	Reduction
13268/11	301HT	311mm	.48mm	

Figure 48.
Graphs Showing Examples of Differences in Strip Shape Caused by Differences in Saddle Settings.



◻ Saddles	5	2	2	5	concave
X Saddles	5	8	8	5	convex

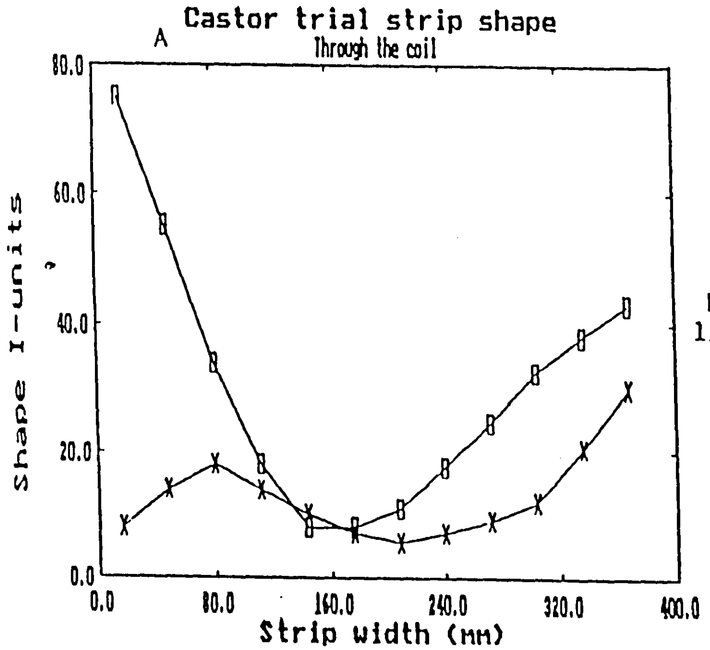
Folio No	Mat'l	Width	Gauge	Reduction
12148/11	301HT	362mm	.3mm	69%



◻ Saddles	5	5	5	5	level
X Saddles	5	2	2	5	concave
◇ Saddles	2	5	5	2	convex
+ Saddles	5	5	2	2	step

Folio No	Mat'l	Width	Gauge	Reduction
11972/11	301HT	422mm	.5mm	57%

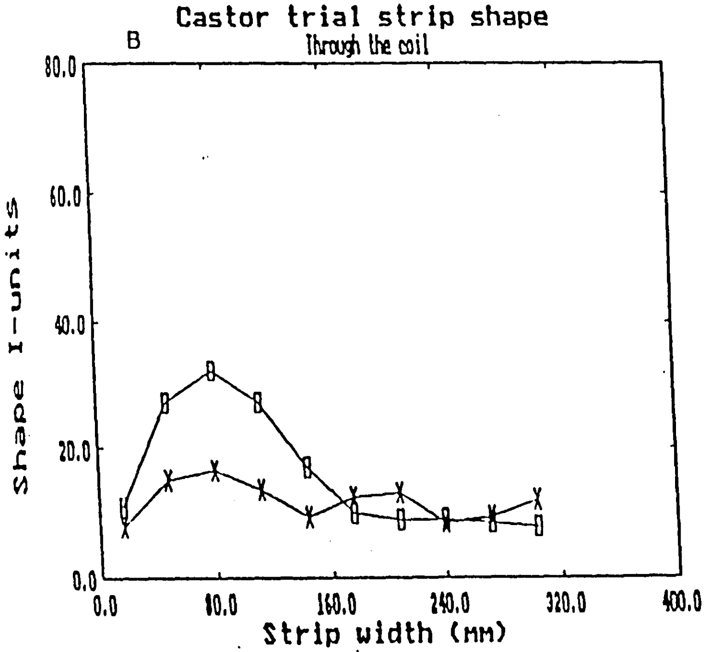
Figure 49.
Graphs Showing Examples of Differences in Strip Shape Caused by Offset Castors.



□ Castors even

X Castors offset

Folio No	Mat'l	Width	Gauge	Reduction
13067/11	301HT	388mm	.3mm	76%



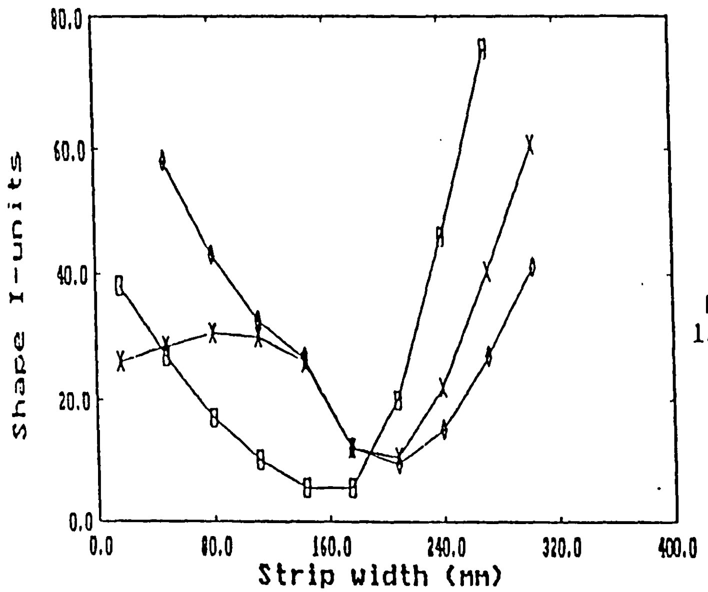
□ End sample castors offset

X Start sample castors offset

Folio No	Mat'l	Width	Gauge	Reduction
13422/11	301HT	327mm	.43mm	45%

Figure 50.
Graphs Showing Examples of Differences in Strip Shape Caused by Rolling Speed Differences.

Speed trial strip shape

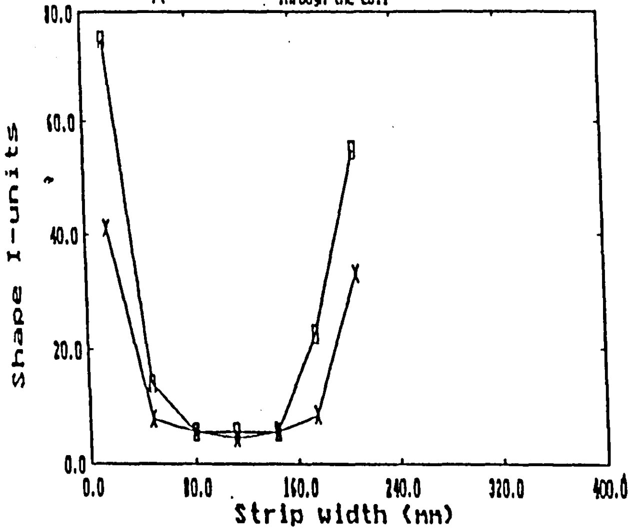


Folio No	Mat'l	Width	Gauge	Reduction
12405/11	301Ht	390mm	.215nm	77%

Figure 51.
Graphs Showing Examples of Differences in Strip shape Caused by Differences in Rolling Tensions.

Tension trial stip shape

A Through the coil



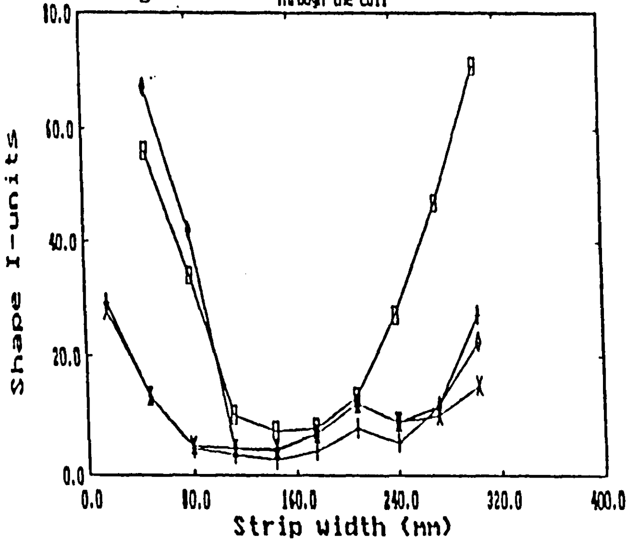
□ Normal tensions

x High tensions

Folio No	Mat'l	Width	Gauge	Reduction
13088/11	301DD	238mm	.25mm	74%

Tension trial stip shape

B Through the coil



□ Start sample }
+ End sample } Normal tensions

◇ Start sample }
x End sample } High tensions

Folio No	Mat'l	Width	Gauge	Reduction
13437/11	301	330mm	.23mm	57%

APPENDIX 1: Shape produced by differential elongations across the strip width.

Edge wave.

Causes for and remedies.

This shape defect is caused by rolling the edges of the strip by a greater percentage than the centre. Edge wave can occur on one or both edges of the strip. The strip can look as if it has a small wave on its edges, with the wave peaks low and the frequency of wave high. High peaks and low frequency wave make the loose edge defect look severe.

Rolling parameters that mostly affect Edge wave, and the action to remove the defects, in order of significance are:

a) First intermediate roll position:

To reduce edge wave the rolls need moving to a position where there is more taper relief on the strip. Small movements of roll position can have significant effect on strip shape.

b) Work roll geometry:

Using camber profiled work rolls reduces edge wave. With chamber rolls the centre of the strip carries more load than the edges. The effective taper of the first intermediate roll is increased.

c) First intermediate roll geometry/strip geometry interaction:

These two parameters combine to have a significant effect on edge wave.

To reduce edge wave use flat profiled incoming strip and steeply angled first intermediate roll tapers.

d) Strip Geometry:

Strip is supplied to LSS with a flat profile or with varying degrees of wedge shape. The flattest supplied strip produces the least edge wave.

e) Strip geometry/first intermediate roll interaction:

Using flat profiled strip and more taper relief combines to reduce edge wave.

f) Work roll Size:

Keeping the work rolls similar in size will help to reduce edge wave.

Front tension:

High front tension will reduce edge wave. A knoll edge of the tensions that can be withstood by the strip is necessary. A rule of thumb given for tensions is not to exceed 60% of the yield stress.

Practical steps.

a) Move the first intermediate rolls to a position where more edge relief is given to the strip.

b) Use camber profiled work rolls or a combination.

c) Keep the work rolls to a similar size.

d) Increase the front tension.

Full (over rolled) centre.

This shape defect is caused by rolling the centre of the strip by a greater percentage reduction than the edges. Rolling centre fullness is time dependant, as rolling time progresses centre fullness increases. There are two reasons for this;

a) The temperature of the mill rolls increases with rolling time until steady state thermal conditions are reached. Increasing temperatures mean that the rolls expand, which in turn reduces the centre of the strip more.

b) Improved lubrication caused by increasing mill speed causes the required rolling load to reduce. With reduced rolling load the mill bends less severely so encouraging full centre.

Because of these time dependant changes, to ensure that good flat strip shape is achieved, the set up strip shape needs to be that of flat edges. The degree of loose edge is based on rolling experience. The roller takes into account the speed, tensions,reductions and material properties when making his judgement.

The rolling parameters that mostly affect full centre strip shape, and the actions to reduce it, in order of significance are as follows.

a) First intermediate roll position.

To reduce centre fullness the first intermediate rolls should be moved so that there is less taper relief on the strip. Small movements of roll position have large effects on strip shape.

b) Work Roll Geometry.

Flat profiled work rolls reduce centre fullness. Mill bending ensures that the strip edges will carry more load then the centre, hence, reducing centre fullness.

c) First intermediate roll geometry/strip geometry interaction.

Use of wedge strip and shallow angled first intermediate roll tapers reduces centre fullness. Wedge strip does not really reduce centre fullness so much as increase the opposite defect of edge ware.

d) Reductions.

Heavy reductions increase mill load. The increased load ensures that the rolls bend more. This bending makes the edges of the strip carry a higher load than the centre so reducing centre fullness.

e) Strip Geometry.

Wedge strip increases edge wave. Because of this centre fullness is reduced.

f) First intermediate roll geometry.

Shallow roll tapers reduce the amount of strip edge relief, and also affect the mill bending. This combination of effects reduces the production of centre fullness.

g) First intermediate roll position/strip geometry interaction.

The combined effects of these parameters increase their individual effects on strip shape. Use of wedge strip and positioning the first intermediate rolls for less taper relief reduces centre fullness.

Practical steps.

a) Move the first intermediate rolls to a position of less taper relief over the strip.

b) Use flat positioned wear rolls or a combination of one.

c) Increase the percentage reduction hence increase the mill load. (this can also be achieved by reducing the back tension)

d) Change the first intermediate roll geometry.

Quarter Buckle.

This defect is caused by complex mill and/or roll bending. Two areas of the strip are reduced at a greater percentage than the rest of the strip. These areas are normally at positions off centre ie quarter positions.

Quarter buckle may occur at one or both sides of the strip shape defect. Quarter buckle and full centre strip shape are closely related.

The rolling parameters that mostly affect quarter buckle strip shape, and the actions to reduce it, in order of significance are as follows:

a) First intermediate roll position.

The difficulty encountered when trying to remove quarter buckle by first intermediate roll position is that, by increasing the amount of tape relief centre fullness is encouraged, and decreasing the amount of taper relief encourages loose edges. No guidance can be given on where to position these rolls. The roller must be aware that the first intermediate rolls position has the greatest effect on quarter buckle.

b) First intermediate roll geometry.

Shallow ground tapers on the first intermediate rolls reduces quarter buckle. To reduce quarter buckle, still retain control on strip direction, and control loose edge strip shape, a double ground taper is recommended. Although not highly significant, the use of flat ground work rolls will have the effect of reducing the first intermediate roll taper.

c) Speed.

Slow rolling speed will produce a more consistent strip shape. The shape that the roller sets up on, will be less likely to alter. Slower rolling speed has been shown to reduce quarter buckle strip shape.

d) Back up roll (saddle) configuration.

Quarter buckle is reduced slightly by setting the saddles to give increased mill centre loading.

e) Load.

Reducing the mill load will reduce quarter buckle. By reducing the load the severity of work roll bending around the first intermediate roll taper is reduced.

This can be achieved by increased tensions or reduced reduction.

Practical Steps.

a) Adjust the first intermediate roll position.

b) Modifying the first intermediate roll geometry. Use first intermediate rolls with a double ground taper.

c) Slow rolling speed.

d) Roll with flat ground work rolls.

e) Set the saddles to give more weight at the mill centre.

f) Reduce the rolling load.

Herring bone (ripple).

This defect is characterised by thin flutes running at an angle in the strip. The mechanism for causing this shape is complex. The material undergoes over rolling and shear stresses across its width at the same time. Rolling tensions play an important role in reducing this defect. High strain peaks are reduced by using high rolling tensions. Shear stresses across the width of the strip are evened out by high tensions.

The rolling parameters that mostly affect Herringbone strip shape, and the actions to reduce it n order of significance are as follows:

a) First intermediate roll position.
With less taper relief loose edges are encouraged and full centre is discouraged. If there is no full centre then the ability of the sheer strains to pull elongated flutes in the strip is removed. Rolling with less taper relief reduces Herringbone.

b) Tensions.
High front tensions reduce herringbone. To accompany high front tensions, the back tension must also be increased to prevent pulling the strip through the rolls.

c) Reductions.

By giving a greater reduction to the strip the rolling load is increased. This increase encourages loose edge and discourages full centre. The localised strain peaks of the work roll bending around the intermediate roll taper is reduced, and the ability of the shear strains to pull flutes into the strip is removed.

d) First intermediate roll geometry.

Any reduction in the severity of bending the work rolls around the first intermediate rolls will reduce herringbone. Any reduction in rolling full centre or quarter buckle will reduce herringbone. To this end the shallow ground or modified tapers will reduce herringbone strip shape.

e) Work roll size.

Keeping the work rolls the same size reduces herringbone. The symmetry of rolling, and the horizontal and vertical bending of the rolls, are affected by roll size. These combine to affect herringbone.

f) Back up roll (saddle) configuration.

Keeping the mill load pattern level will help to reduce herringbone. Differences in stresses across the strip are reduced, which will discourage herringbone.

Practical steps:

a) Position the first intermediate rolls as to remove centre fullness.

b) Keep the front rolling tension high.

c) Increase reductions so reducing fullness.

d) Use shallow or modified double taper first intermediate roll geometry.

e) Keep the work rolls similar in size.

f) Keep the saddle settings level.

Coilset.

Coilset, is the tendency for the strip to curl in its longitudinal direction. What causes coilset is a difference in stress distribution through the thickness of the strip. There are a number of rolling faults that create this differential stress distribution, they are as follows:

(a) Lubrication/cooling differences between the top and bottom strip surfaces.

(b) Different work roll diameters.

(c) Non-level strip pass line height.

(d) Uneven material properties.

(e) Difference in top and bottom strip surface speed.

(f) Different work roll surface finishes.

There are rolling variables which do not cause coilset but make the process more sensitive to it. The most notable of these is rolling load.

Rolling parameters that mostly affect coilset strip shape and the actions to reduce it, in order of significance are as follows.

a) First intermediate roll position.

   Positioning the first intermediate roll to give less taper relief reduces coilset. The reason for this is that coilset and full centre are related by horizontal roll bending. Less taper relief reduces full centre.

b) Reductions.

   Decreasing the rolling load by decreasing the reductions makes the rolling process less sensitive to coilset. The work rolls do not bend so severely horizontally. The stress distribution differences are less severe because the surface stresses are lower.

c) Strip geometry.

   Wedge strip encourages loose edge, this reduces the likelihood of full centre, so reducing coilset.

d) Work roll geometry.

The rolling set up which reduces full centre, that of using flat profiled work rolls, also reduces coilset.

e) First intermediate roll/strip geometry interaction.

Positioning the first intermediate rolls to give less taper relief, and using wedge strip interaction increases the amount of loose edge. This ensures a reduction in centre fullness with the associated reduction in coilset.

f) First intermediate roll geometry/strip geometry interaction.

The combination that reduces coilset is that of using steep tapered first intermediate roll profiles, and wedge strip.

g) Reduction/back tension interaction.

These two parameters interact to reduce coilset more than they would do individually. A low reduction, which reduces rolling load, with a low back tension, which slightly increases rolling load, reduces coilset.

h) Speed.

High rolling speed reduces rolling load and, although centre fullness is increased, the sensitivity of the strip to coilset producing faults is reduced. Lubrication conditions are evened out between the strip surfaces with high rolling speeds.

Practical steps:

a) Position the first intermediate rolls to give less taper relief.

b) Reduce the rolling load.

c) Use flat ground work rolling which are similar in size.

d) Keep the pass line height level.

e) Ensure even lubrication/cooling conditions.

f) Low back tension.

g) High rolling speed.

Cross camber.

Cross camber is the tendency of the strip to form a curve across its width, that is, to form a gutter. This shape is caused by a difference in stress distribution through thickness of the strip. The formation of coilset is attributed to crossing of the rolls in contact with the strip. To isolate a single cause of coilset is difficult, lateral material flow across the roll bite may account for some of it. Coilset is closely related to cross camber. To remove cross camber follow the same conditions as for removing coilset.

Twist.

This is a form of negative and positive cross camber occurring at the same time. Twist is caused by a through thickness differential stress pattern which changes across the strip width. The cause of twist is generally attributed to differences in work roll surface finish. Other factors such as horizontal roll bending, lubrication differences and lateral material flow may affect twist. To remove twist follow the conditions as for removing coilset.

General rolling practices to help improve strip shape.

a) Ensure consistent grinding of all mill rolls. A recommended target of $3\mu m$ roll profile accuracy should be aimed for. That is, the rolls should exhibit no more than $3\mu m$ taper. The rolls, if cambered, should be within $3\mu m$ as their stated camber, the roll camber should be central. The rolls should exhibit consistent surface finish with no chatter marks. Any inconsistency will encourage coilset, cross camber and twist.

b) First intermediate rolls with a double tapered profile should be used (after further research this profile may be further improved).

c) Generally high rolling tensions, especially front, will reduce strip shape defects. Tensions of up to 50% of stress yield can be used.

d) Reduced last pass rolling speed will ensure a more consistent strip shape. The shape rolled will be near to that which the operator starts with.

e) Keeping the mill accurately aligned will help the strip to run correctly. Any deviation of line causes strip shape problems. Periodic checks on mill alignment should be made.

f) Using similar sized work rolls make the rolling process more consistent and generally help to improve strip shape.

Recommended practices for rolling throughout a sequence.

Rolling parameters (variables) have an effect, not only on a single rolling pass but, cumulatively throughout a complete rolling sequence. Within material properties ranges it is possible to recommend certain rolling practices.

Recommended practices:

a) Material type 316 Austenitic stainless.

Dimensions 0.312m wide.

Rolled from 1.22mm to 0.305mm a 75% reduction.

Middle strip no wedge.

Rolling mill FZ3

Work rolls

Roll throughout the sequence with one flat and one cambered work roll.

First intermediate roll position:

Aim for slightly full strip shape throughout the sequence, then for good flat last pass strip shape.

Saddle settings:

Preferred settings may change dependent on the rolls in the mill. On the information received to date the preferred saddle settings are those which give convex loading. Setting at 5,8,8,5.

Speed:

Reduced last press rolling speed of 80 metres/minute will help to produce better strip shape.

Reductions:

These have little effect throughout the sequence on strip shape as long as the last pass is kept reasonably low. A six or seven pass rolling sequence with the last press being approximately 7% or less will give good shape.

Tensions:

High tensions improve the strip shape. On the low tension setting the Amps should be 600A for Back tension and 700A for Front tension for the last pass. These current settings relate to 15,000 lbs (6,782 kg) and 17,500 lbs (7916 kg). These tensions relate to 60% of the yield strength. These tension settings can be used throughout the rolling sequence. Using these settings product variation will be reproducible. Good strip quality of below 30 I-units with care will be predictable. Average rolled shape without these settings can be over 50 I-units. 50 I-units is recognised as average for rolled strip shape.

b) Material type 316 Austenitic stainless.

Dimensions .320mm

Rolled from o.406 to 0.179mm a 569% reduction.

Wedge strip-0.01mm wedge.

Rolling mill FZ1.

Work rolls.

Roll throughout the sequence with two flat work rolls. This is the most important parameter affecting strip shape on this job.

First intermediate roll position:

Aim for good strip shape throughout the rolling sequence.

Saddle settings:

On this job and on this mill, the saddle settings have a significant affect on strip shape. Holding the saddles to give a line only increasing load across the mill dependent on the wedge of the strip is best. Where the thickest edge of the strip is, there should be a wider roll gap and vice-versa. Saddle settings of 2,3,4,5 should be used.

Tensions:

At 60% of the yield strength of the material on the last pass 5880 lbs (2830 kg) max front tension should be used.

Using these settings product variation will be reduced and consistent strip shape produced. Reductions in rolling speed from those normally finished on, 115 meters/minute will further improve strip shape.

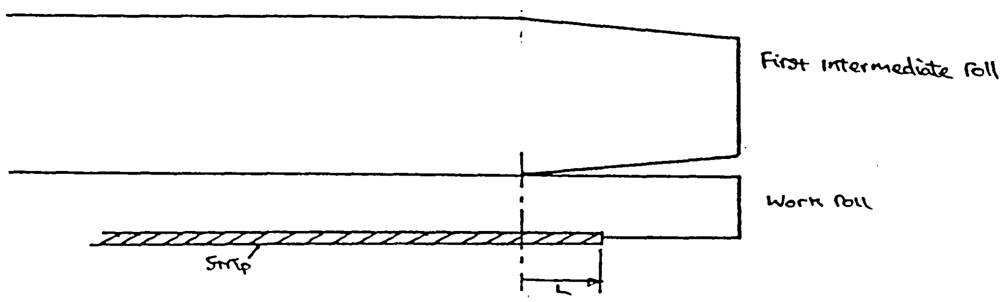
APPENDIX 2

Model of first intermediate roll effects on work roll bending.

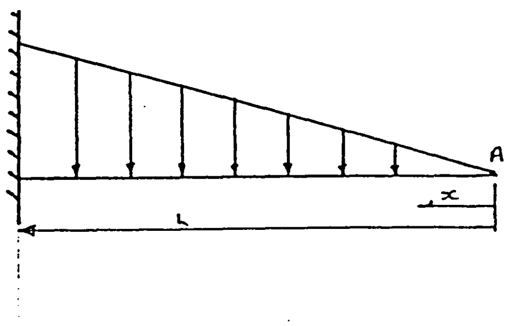
To confirm the strain results showing the dominat effect of taper position on strains experienced by the roll a simple model is here forwarded to show the relationship between "y" the distance that the taper allows the roll to move.

"W" the maximum load applied

"L" the length or taper position



Assuming compression between the strip and work roll and the first intermediate roll and work roll. The overhang of the strip will exert a force. Assuming that the force exerted reduces in a linear manner then a simple beam approximation of the system would be as follows.



A general formula is required to express the relationships involved.

From Beam Theory $$EI \frac{d^2y}{dx^2} = -BM$$

where F = Youngs Modulus

I = Second moment of area

BM = Bending movement

$\frac{d^2y}{dx^2}$ = Rate of change of beam curve

To solve this a general formula to express the bending moments is required.

Let x be same distance measured from Point A

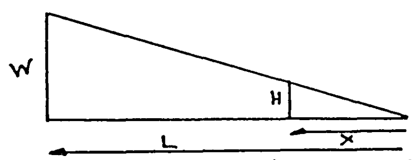
Moment = Force x distance

For the triangular loading situation the distance used is that of the centroid. When measuring to the centroid from the apex of a triangle its distance is found to be 2/3 of the length.

The area of the triangle is the total load, therefore for the general solution we need the load at any position.

From similar triangles the relationship can be found

$$\frac{W}{L} = \frac{H}{x}$$



Therefore the load condition or area of the triangle is

$$\frac{Wx}{L} \cdot \frac{x}{2} = \frac{Wx^2}{2L}$$

$$\text{BM formula} = \frac{Wx^2}{2L} \cdot \frac{2x}{3} = \frac{Wx^3}{3L}$$

Solving $$EI \iint \frac{d^2y}{dx^2} = \iint -BM\,dx$$

$$EI\frac{dy}{dx} = \frac{-Wx^4}{12L} + A$$

$$EI\ y = -\frac{Wx^5}{60L} + Ax + B$$

To find the constraints of integration, apply the Boundry conditions

at $x = L$ $\quad y = O$
at $x = L$ $\quad \frac{dy}{dx} = O$

$$\text{from } EI\ dy = -\frac{Wx^4}{12L} + A$$

$$O = -\frac{WL^3}{12} + A$$

$$A = \frac{WL^3}{12}$$

$$\text{from } EIy = -\frac{Wx^5}{60} + Ax + B$$

$$O = -\frac{WL^4}{60} + \frac{WL^4}{12} + B$$

$$B = -\frac{WL^4}{15}$$

The general relationship is:

$$EIy = -\frac{Wx^5}{60L} + \frac{WL^3x}{12} - \frac{WL^4}{15}$$

If we allow x = o ie. at the beam end

$$EIy = -\frac{WL^4}{15}$$

from this it is clear that

y is proportional to W
and y is proportional to L^4.

The quadratic term shows the domination by the length over other factors in producing bending.

For a more accurate model the loading conditions can be changed, however, the model will only be refined not radically altered in its relationships.

The model confirms that the bending as recorded from strain measurements is dominated by the position of the first intermediate rolls.