COMPUTER AIDED FORM ROLL DESIGN

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SUMMARY

Cold roll forming is an extremely important but little studied sheet metal forming process. In this thesis, the process of cold roll forming is introduced and it is seen that form roll design is central to the cold roll forming process. The conventional design and manufacture of form rolls is discussed and it is observed that surrounding the design process are a number of activities which although peripheral are time consuming and a possible source of error. A CAD/CAM system is described which alleviates many of the problems traditional to form roll design. New techniques for the calculation of strip length and controlling the means of forming bends are detailed. The CAD/CAM system's advantages and limitations are discussed and, whilst the system has numerous significant advantages, its principal limitation can be said to be the need to manufacture form rolls and test them on a mill before a design can be stated satisfactory.

A survey of the previous theoretical and experimental analysis of cold roll forming is presented and is found to be limited. By considering the previous work, a method of numerical analysis of the cold roll forming process is proposed based on a minimum energy approach. Parallel to the numerical analysis, a comprehensive range of software has been developed to enhance the designers visualisation of the effects of his form roll design. A complementary approach to the analysis of form roll design is the generation of form roll design, a method for the partial generation of designs is described. It is suggested that the two approachs should continue in parallel and that the limitation of each approach is knowledge of the cold roll forming process. Hence, an initial experimental investigation of the rolling of channel sections is described. Finally, areas of potential future work are discussed.

KEYWORDS : . COLD ROLL FORMING

FORM ROLL DESIGN

FLOWER PATTERN DESIGN

COMPUTER AIDED DESIGN

NUMERICAL ANALYSIS

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CONTENTS

LIST OF FIGURES

FIGURES

LIST OF TABLES

TABLE

LIST OF PLATES

GLOSSARY

"Brick" element :	Element of metal in the numeric integration of power, the suffix "brick" discrimates from the term element, (described below)
CAD :	Computer aided design.
CAM :	Computer aided manufacture.
(Roll) Centre to : centre distance	The vertical distance between the centre lines of the top and bottom rolls.
Cold roll forming :	A continuous process of progressive bending metals in a straight line without changing the material thickness using successive sets of rotating tools.
Downstream :	Towards the finished section.
Element :	A (linear or circular) segment of the finished section.
Finished section or : section	The end product of the cold roll forming process.
Flower pattern or : flower plan	The nominal neutral axis representation of the metal shape at each stage in the cold roll forming process.
Form rolls or rolls :	The tooling used to impart shape into the metal strip in the cold roll forming procress.

N.C : Numerical control

Pass or stage : A set of (between two and four) form rolls which impart shape into the metal strip.

Pass height : The vertical distance between the centre of the bottom roll and the base of the section.

Pass length or interpass length : The horizontal distance between two successive passes of the cold roll forming process.

Rolling mill or mill : The machine on which the rolls are mounted.

Side rolls : Rolls with their axis vertical.

Tag : The name given to the metal which has been deformed from flat strip but has not reached the finished section shape.

Upstream : Towards the flat strip.

CHAPTER 1

INTRODUCTION

The application of the computer to the design process is relatively modern but already well established. Almost all of the advantages of the computer are relevant to design. In particular the computer can carry out large numbers of complex calculations effortlessly, store large amounts of information and retrieve it quickly, produce high quality graphical and text documentation and allow simple editing to an existing design. This project will examine how the computer has been applied to the design of tooling for one of the more traditional industries, cold roll forming.

Cold roll forming is the name given to a process whereby shape is imparted into a sheet metal strip, without changing the material thickness, by passing the strip through successive sets of rotating tools. The process has existed since the early part of the century and has evolved into, by weight, one of the most important of all metal forming processes.

Roll formed section manufacturers are obviously looking for ways of reducing lead times and efficiently producing form rolls. Therefore, not surprisingly, cold roll forming is one of the many industries where CAD/CAM (computer aided design/computer aided manufacture) techniques have been applied and CAD/CAM systems developed. Such systems have had numerous real advantages, particularly by reducing lead times and by automating the relatively routine tasks, which are time consuming but peripheral to the form roll design process.

Form roll design is an idiosyncratic process where opinions differ from company to company as to what facilities a form roll CAD/CAM system should offer. Thus, in general, the development of form roll CAD/CAM systems has been instigated by individual cold roll forming organisations seeking a system which will suit their particular needs. To a large extent, then, such systems have effectively computerised existing procedures and standards within a particular cold roll forming organisation. Aston University have acted in collaboration with a leading manufacturer of cold roll formed sections to develop a computer aided design package for form roll production[1]. This package has been developed and augmented by a computer aided manufacture package for the production of numerical control (N.C) tapes and implemented as a CAD/CAM system on a single user workstation[2]. The increasing acceptance of the CAD/CAM system and the rapid expansion of the collaborative organisation has provided the need for a multi-user capability within the CAD/CAM system.

It is desirable and perhaps inevitable that having automated the existing procedures within a cold roll forming organisation, that the CAD/CAM system will be further developed by applying existing knowledge or techniques which had not previously employed within that organisation. As an example, in the manufacture of form rolls many CAD/CAM users have taken the logical step of installing N.C machinery to replace the previously used copy lathes. However, with the design of form rolls the range of conventional theory is extremely limited. Therefore, form roll design using the CAD/CAM system is still based on the individual designers experience of material properties, mill properties and the cold roll forming process.

When the conventional theory has been exhausted new methods have to be developed for the analysis of form rolls. In general, two methods by which the computer is commonly applied to aid the design process are by providing the designer with an enhanced visualisation (for instance through surface modelling or solid modelling) and by numerical analysis techniques (such as finite element methods). In general, it can be said that, whilst the computer has revolutionised the design and manufacture of form rolls, its capacity for the analysis of form roll design has remained largely untouched.

This research then is primarily concerned with the application of existing knowledge to the design of form rolls and the development of new techniques (both visual and numerical) for the analysis of form roll design. Specifically work was carried out in the following main areas.

(1) The implementation of the CAD/CAM package on a multi user system.

(2) A study of cold roll forming, particularly the theoretical and experimental analysis of form roll design.

(3) The isolation of existing techniques, relevant to the design of form rolls and research into their scope of application within a computer aided system for the design of form rolls.

(4) Research into the formulation of new computer aided techniques both for the analysis and improvement of form roll design.

CHAPTER 2

COLD ROLL FORMING

2.1 DEFINITION OF COLD ROLL FORMING

As a working definition, cold roll forming can be said to be, a continuous process of progressively bending metals in a straight line without changing the materials thickness using successive sets of rotating tools. In practice, the materials thickness will alter due to material thinning around bends and the rolls may be moved slightly out of line when forming certain sections.

As such, cold roll forming provides a very useful sheet metal forming process, capable of consistently and accurately producing a wide range of profiles in a wide range of ferrous and non ferrous materials with little restriction on length.

The wide range of potential applications can be indicated by considering North America where it has been estimated that more metal is roll formed each year than is produced by, die casting, extrusion, closed die forging and powder metallurgy[3], combined.

2.2 THE COLD ROLL FORMING PROCESS

A feature of the cold roll forming process is the large variety of sections that can be produced using standard equipment by varying tooling and rolling conditions. The elements of the cold roll forming process can be grouped and described under 4 main headings:

(1) Roll form tooling

(2) The rolling mill

(3) Auxiliary equipment

(4) Operating conditions

2.2.1 ROLL FORM TOOLING

The primary purpose of any tooling is to produce a required form in some material. In metal cutting this implies the removal of metal, in metal forming the shape is produced by causing plastic deformation in some or all of the material. In cold roll forming the finished section shape is produced by progressively bending from flat strip. Form is created in the metal stage by stage by using successive sets of rotating tools, or as they are more commonly known rolls (or form rolls). A set consists of between two and four rolls, (namely the top roll, the bottom roll and optionally the left and right hand side rolls). Side rolls are rolls with their axes vertical which are useful for producing vertical or near vertical legs in a section. Figure 2.1 shows a set of top and bottom rolls, Figure 2.2 shows a set of top, bottom and side rolls.

A secondary purpose of the form rolls is that they produce the motivation to drive the metal strip through the mill by friction between certain surfaces of the roll contour and the metal strip.

An exceptional type of form roll is the internal roll, which is shown in Figure 2.3. This is used as a last resort in cases where a section cannot be accurately formed using conventional top and bottom rolls. The internal roll is obviously more complex to manufacture than conventional rolls and also has significant disadvantages in its use.

Top and bottom rolls may occasionally be split into two or more pieces, (Figure 2.4). This allows a variable range of sections to be produced by separating the split rolls by spacers, hence reducing tooling costs. Split rolls in addition may be easier to machine in some case and allows selected parts of a roll to be replaced.

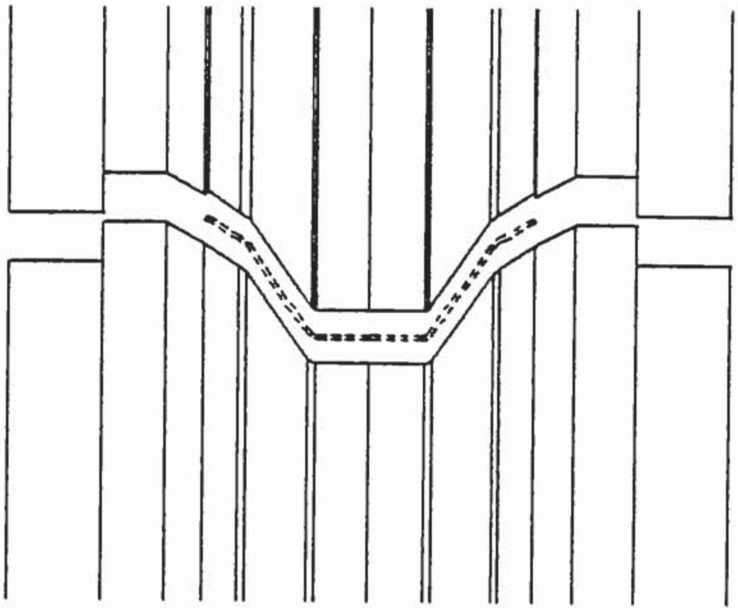


FIGURE 2.1 TOP AND BOTTOM ROLLS

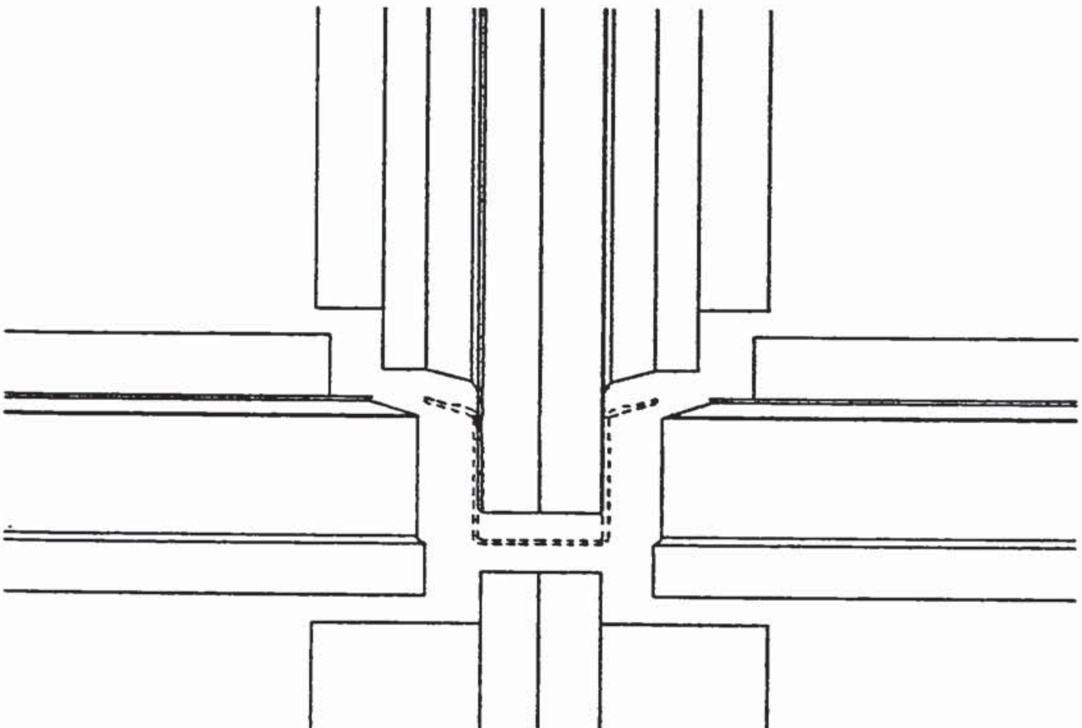


FIGURE 2.2 TOP , BOTTOM AND SIDE ROLLS

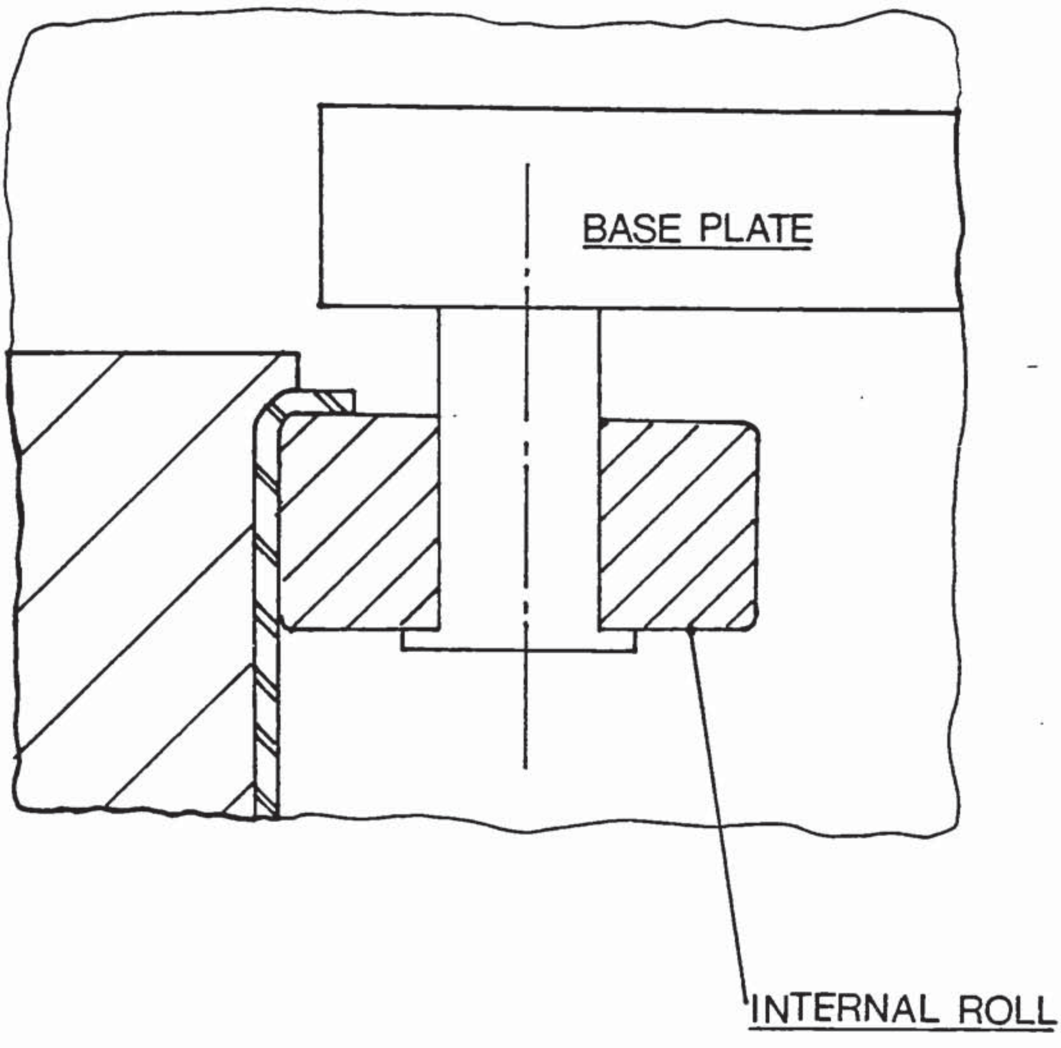


FIGURE 2.3 EXAMPLE OF THE USE OF INTERNAL ROLLS

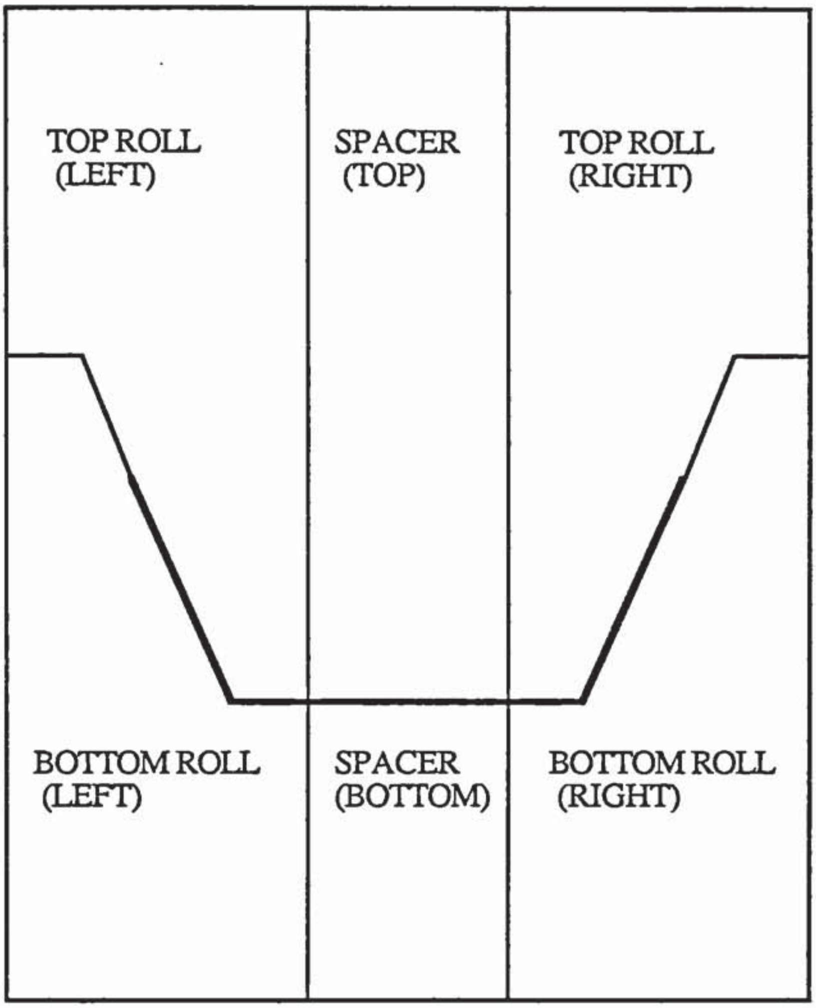


FIGURE 2.4 EXAMPLE OF THE USE OF SPLIT ROLLS FOR THE PRODUCTION OF CHANNEL SECTION WITH VARYING BASE WIDTHS

2.2.2 THE ROLLING MILL

Having considered in the previous section the tooling which imparts form into cold rolled sections, it will be enlightening to briefly describe the machine on which the rolls are mounted, the mill or rolling mill. Furthermore it will be seen later, the rolling mill must be considered when form rolls are designed. Whilst a detailed analysis of rolling mill design would be inappropriate, those seeking a more exhaustive description of the mechanical design of general rolling mills could consult Tsclikov and Smirnov[4].

The primary purpose of the rolling mill is obviously to provide the framework on which the form rolls can be mounted, driven and controlled. Mills can be designed for producing one specific section[5] or, more commonly for producing any section, within the constraints on power, size of section and number of passes imposed by the mill design.

The elements of a rolling mill can be described in three main sections

(1) Structure
(2) Power and transmission
(3) Executive functions

2.2.2.1 STRUCTURE

The machines structure consists of two main elements, the base and the roll stands. The base is only critical in that it should provide sufficient rigidity to restrict roll stand deflections to a minimum. In addition, common sense dictates a design which eases maintenance whilst restricting access to moving parts.

The roll stands support the spindles on which the form rolls are mounted. The stands contain the mechanisms by which roll positions can be adjusted (or set) relative to one another. Roll stands are traditionally described as being of two main types overhung

or spindle (Figures 2.5A and 2.5B). In practice, the spindle seems to be by far the most common since, whilst the overhung stand facilitates fast change over of rolls it provides considerably less rigidity.

The size and complexity of section which can be produced on any mill is constrained by the inter stand distance and the number of available passes. Whilst inter-stand distances are fixed the number of passes available can be made more flexible by designing the mills structure in a modular fashion allowing additional passes to be 'bolted on' to a mill.

2.2.2.2 POWER AND TRANSMISSION

The form rolls are driven by an electric motor, commonly of between ten and one hundred horsepower, through some form of transmission system. Power capacity can provide a constraint on the sections which can be rolled, on a machine, particularly with thicker materials.

Individual passes are driven from the motor by some form of linkage, commonly some form of chaining. The rolling speed is important both technologically and economically, different materials and different sections require different rolling speeds, thus a general purpose mill requires some form of gearing and/or speed controller to allow variation in rolling speed.

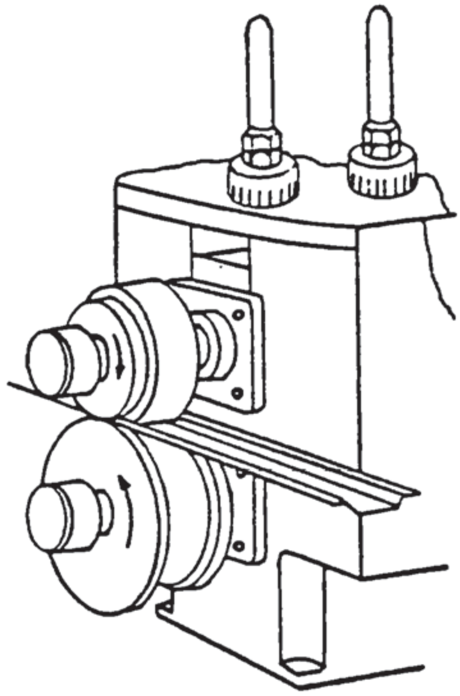


FIGURE 2.5A   OVERHUNG ROLL STAND

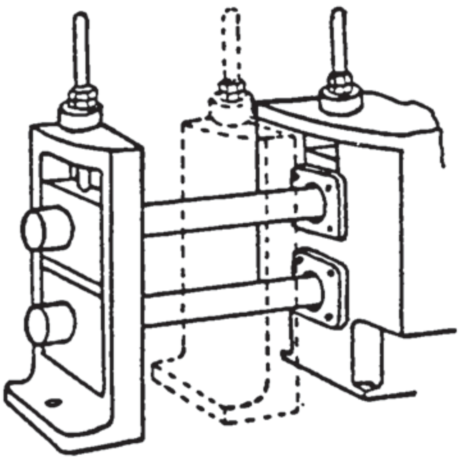


FIGURE 2.5B   SPINDLE TYPE ROLL STAND

2.2.2.3 EXECUTIVE FUNCTIONS

The previous sections described how rolls are mounted and driven, the final element in a rolling mill is clearly to incorporate control (or executive) functions, for initiating and terminating rolling and for synchronising the process with auxiliary equipment.

Control systems for cold roll forming lines vary in sophistication from manually operated hard wired controllers to mini-computer based direct numerical control systems[6]. State of the art lines allow input of rolling speed, number of components and length of section and synchronise punching operations, shear operations and welding operations to provide completely automatic cold roll forming. It is easy to imagine how computer controlled lines could eventually be linked to a production control system to allow management functions such as production monitoring, stock control and production scheduling.

2.2.3 AUXILIARY EQUIPMENT

All rolling mills are combined with auxiliary equipment of some description, to either, ensure as continuous a flow of as level a strip as possible to pass through the mill or to alter the nature of the finished product. Whilst, the equipment mentioned below cannot be considered a comprehensive listing, it includes the more widely used equipment and is representative of the diversity of equipment available.

Ensuring as continuous a flow of as level a strip as possible, is obviously important in both a technological and an economic sense. Strip is transported and stored in coils, the coil to be rolled is first mounted onto a strip decoiler which rotates and unwinds the coils prior to passing through the rolls. Depending on the material used and the section required it may be necessary to pass it through straightening gear. These consist of a series of flat rolls, which are offset and which progressively increase the longitudinal radius of curvature until any residual curvature in the section is effectively eliminated.

The major impediment to continuous flow of strip occurs when a coil ends. A method of overcoming this is by creating a stockpile of stored metal between the decoiler and the mill in a loop accumulator, this allows sufficient time for a new coil to be positioned and the ends of the coils to be butt welded together, this allowing virtual continuous production.

Cold roll forming is a very flexible process, virtually any profile of constant thickness can be produced, auxiliary equipment can also be used to alter the nature of the section, hence giving the process more flexibility. To ease transportation, finished sections are either cut to length or formed into a coil. Finished sections are cut to length using a shear , this can be done by stopping the mill, or by using a 'flying shear', where the shear cuts whilst moving at the same velocity as the strip, thus allowing continuous production. Welding equipment can also be incorporated into the mill an example being seam welding (for instance in tube rolling processes). Also sections may be notched, pierced or embossed before or after rolling thus allowing a diverse range of products to be produced without the need for finishing operations.

2.2.4 OPERATING CONDITIONS

The previous sections have introduced the process of cold roll forming and the tooling and equipment required in cold roll forming. It remains to describe the conditions under which roll forming is carried out. The operating conditions will be described under three headings:

(I) Roll lubrication

(II) Roll quality and variation in material properties

(III) Roll setting

2.2.4.1 LUBRICATION

The decision, of weather to use a lubricant, and if so the type of lubricant and the method of application must be given careful consideration on the basis of the type of metal being rolled, the rolling speed, the tooling material and the likelihood of damage to the tooling and material surfaces.

Careful lubricant selection can reduce sectional distortion due to heat, it can give a better surface finish by reducing scuffing and by "flushing" away debris from between the rolls, additionally it can reduce wear and prolong tool life. However, whilst, the application of a lubricant can have these numerous significant advantages, unnecessary or incorrect application of a lubricant can similarly result in significant disadvantages such as sectional distortion due to differential friction, surface defects such as white rust, staining, blushing, blistering and peeling and the need for auxiliary degreasing operations; thus many sections are rolled without lubricant.

There are numerous types of lubricant for cold roll forming and several methods of application of lubricant, it would be inappropriate to detail these although those requiring further detailed information should consult the papers written by Ivaska, tabulating the type of lubricant suitable for specific metals[7] and investigating and analysing the most common lubrication problems[8].

2.2.4.2 <u>ROLL QUALITY AND VARIATION IN MATERIAL PROPERTIES</u>

Two factors, which contribute to the sectional quality, but which are difficult to accommodate within the tooling design are the roll quality and the variation in material properties. Roll form tooling is necessarily designed on assumptions regarding the material being formed. In practice the material properties will vary from these nominal values, thus the finished section for the same tooling will alter. This is a particular problem where the materials tendency to return to its original shape (springback) is altered or the material thickness alters.

Roll quality can affect the finished section in two ways. Firstly, as the roll surface finish deteriorates the finished section acquires marks and surface defects. Secondly if the rolls have been inaccurately machined or the rolls have worn then the finished section profile will clearly differ from the required finished section.

2.2.4.3 <u>SETTING</u>

The setter, the person who sets the rolls on the mill, provides the link between the design and development of tooling and the finished section production. The importance of roll setting should not be underestimated, a good setter can salvage a poor design and can suggest those minor modifications to the design which will improve the final section quality. Similarly, the quality of roll design can become irrelevant if the rolls have been set carelessly. Thus, a setter must combine a considerable level of practical skill with a thorough knowledge of the forming process.

However, whilst setting is vital to section production, it should not be assumed that an inspired setter can replace the roll designers skill. Indeed, even when a technologically good section can be formed by careful setting, the amount of time spent developing and setting rolls can be that large that the design can be stated unsatisfactory from an economic viewpoint. Thus whilst quality of design is a nebulous concept one of the few methods which can be used for quantification is to calculate the ratio of rolling time to the setting time.

In practice, rolls are normally positioned on the mill one pass at a time. As each pass is installed strip is fed through the rolls and bent towards the required shape. The setter will attempt to ensure that the section exiting the pass is as free from sectional defects as is possible. Thus the roll stages are built up successively with minor modifications being made to the roll design as is required. Finally, the setter must attempt to produce a finished section of a suitable quality, this stage, of course forming the ultimate test of the roll design.

There has been little scientific study of the factors available and the methods employed by the setter in achieving the best section from any given roll design. Thus roll setting has remained a mystery in a similar way to roll design. So, whilst there are doubtless subtler factors involved, the main methods employed by the setter seem to be moving the passes out of line, varying roll pressures, varying the "spacing" of passes and using interpass forming devices.

2.3 ADVANTAGES OF COLD ROLL FORMING

The previous sections have defined and described the process of cold roll forming, this should provide the background for understanding the advantages (listed below) cold roll forming has over rival techniques such as extrusion, press braking or hot rolled sections.

Firstly, the process is considerably more flexible than the other processes. Virtually any profile of constant thickness can be produced, including many which could not be produced by rival processes. The only restriction on lengths of section is that imposed by transport or handleability. As will be detailed later a large range of metals can be formed by cold roll forming.

Cold roll forming can be a highly economic process, particularly where large quantities of a particular section are required. The process requires quite high initial costs for tooling but then achieves very high productivity rates with small variable costs. Also with cold roll forming it is possible to produce exact lengths, thus reducing wastage, when compared to extrusion, say. Transport costs can also be substantially reduced since cold rolled sections will often be lighter weight than those produced by rival processes. Profiles produced by cold roll forming often have a more aesthetically pleasing appearance than those produced by rival processes. This is because the metal largely retains its initial surface conditions, since, the metal remains at low temperatures during processing and also the manner of forming is a smooth, flowing, action. Indeed it is quite possible to roll precoated or prepainted strip, thus elimating subsequent operations.

Technologically, cold formed sections are often superior to those produced by rival processes. Firstly the diversity of profile which may be produced by form rolling means that profiles with improved sectional properties and lower weight may be designed. An interesting comparison between a hot rolled and a cold rolled section is given by the cold rolled sections association[9], the cold rolled section has superior sectional properties whilst giving a weight saving of over 24%. In addition material properties can be improved by the work done in cold roll forming, (Karren[10]).

2.4 MATERIALS FOR COLD ROLL FORMING

In general, metals with sufficient ductility to be formed by cold forming methods are suitable for the cold roll forming process. These include ferrous metals such as low carbon steels, medium carbon steels, alloy steels and stainless steels and non-ferrous metals such as aluminium, aluminium alloys, copper, copper alloys and zinc alloys.

Within this wide range, information on the chemical composition, mechanical properties and geometric accuracy of specific materials is contained in the respective British Standard. In particular, BS 1449 contains information on carbon and stainless steel, BS 1470 contains information on aluminium and aluminium alloys and BS 2870 contains information on copper and copper alloys.

Titanium can also be roll formed, however its poor forming characteristics at room temperature make it more suitable for hot roll forming. Foster[11] showed that the minimum bend radius (a good indication of formability) could be substantially reduced (by up to 70%) if forming takes place at an elevated temperature.

High strength low alloy (HSLA) steels are being more commonly utilised, particularly in the transportation industry. Ferry[12] describes the difficulties in roll forming HSLA steels as well as the techniques used to overcome these problems, in an example from the automotive industry .Beecher[13] documents an example from the railway industry, whilst describing a roll forming system for rolling heavy gauge HSLA steels.

Additionally a wide range of pre-coated material can be cold roll formed. These can, of course, eliminate costly finishing operations and improve a section's appearance and performance. Common pre-coatings include zinc coating, aluminising, plastic coating and pre-painting. In thin sections the ability to roll galvanised metal is important because distortion would otherwise occur in the high temperatures of hot dip galvanising.

Specific problems which occur when roll forming coated materials mainly revolve around damaging the coating. Simonsen[14] describes techniques used to minimise such problems, including, high quality finished or polished rolls, special lubricants or temporary plastic films on the strip applied in either laminate or liquid strippable form.

CHAPTER 3

CONVENTIONAL FORM ROLL DESIGN AND MANUFACTURE

3.1 INTRODUCTION

Form rolls are, of course, the tooling used in the roll forming process to impart shape into strip to produce some required finished section. As such, clearly they are central to the form rolling process and their correct design and efficient manufacture is of the utmost importance. This chapter's purpose is to describe and assess traditional methods of form roll design and also to introduce and describe nomenclature which will be used in future chapters.

The design and manufacture of form rolls can be most conveniently considered as a series of clearly defined sequential stages. Namely:

1. Finished section design
2. Flower pattern design
3. Roll design
4. Wire template production
5. Roll machining

Whilst each "job" goes through all of these stages it is a mistake to assume that form roll design is routine. In practice each job will provide unique problems to the designer and requires imaginative and often innovative solutions combined with a good knowledge of material and process properties.

3.2 FINISHED SECTION DESIGN

Clearly the initial input to the form roll production process must be (paradoxically) some finished shape to work towards. It is perhaps misleading to refer to this as the finished section design since very often the section has already been designed to meet the requirements of its eventual usage and the form roll designer takes this definition as his starting point.

However it is often desirable for the finished section designer to work closely with the form roll designer since, as with most fields of engineering, it is important to design with manufacture in mind. It is frequently stated that designing for manufacture is particularly important when designing sections suitable for cold roll forming since an intelligent section design will be easier (and hence cheaper) to roll and will also produce a better quality section.

The great majority of section designs consist of two types of element, namely linear and circular elements, although more complex shapes can be rolled, clearly the design and manufacture of form rolls will become correspondingly more complex.

One of the initial routine exercises performed by the form roll designer is to calculate the strip length, this will determine the rolling mills which the section can be produced on and will allow the strip to be ordered at an early stage. The method by which the strip length is calculated will be detailed later.

3.3 FLOWER PATTERN DESIGN

The flower pattern was originally the name given to the cumulative pictorial representation of the strips nominal neutral axis at each stage in the roll forming process (Vanderploeg[15]). This name has now come to describe the whole process of designing the manner by which metal is bent from flat strip up to the final finished section.

Form roll design has been referred to as the "black art" of metal forming, a comment on the lack of guiding scientific principles for flower pattern designers. Certainly, considering the vast amount of metal processed by this technique the conventional theory is very restricted, being limited to a small number of empiricisms whose validity has been questioned. In practice, most flower pattern design is based on the designers, necessarily incomplete, knowledge of material properties, mill properties and the cold roll forming process. In short, flower pattern design is based on experience and probably nowhere is the definition of experience as being the sum total of previous disasters more applicable than flower pattern design.

The importance of the flower pattern should not be underestimated, the flower pattern is the crux of roll design, the remainder of the roll design is relatively routine but the flower pattern requires a significant level of innovative thinking and decision making. A flower pattern design can be quantified by identifying each bend on the finished section and describing the amount of bending to take place and the means of forming of each bend at each pass in the roll forming process.

Flower pattern design can be conveniently considered by splitting into four main areas.

(I) Orientation of section

(II) Sequencing of bends

(III) Amount of bending at each stage

(IV) Means of forming bends

3.3.1 ORIENTATION OF SECTION

Any sections orientation is determined by a number of (often conflicting) considerations, careless orientation may result in tooling, production or quality problems. As with many other aspects of roll forming, section orientation is often a compromise, some of the factors influencing the designer's final decision are discussed below.

Whenever a bend is not formed by both a male and a female roll it is termed a blind bend or fresh air bend, such bends often result in sectional inaccuracy and are thus to be avoided if at all possible, careful orientation may reduce fresh air bending. (Figure 3.1 illustrates what is meant by fresh air bending.)

Springback (the metal's tendency to return to its original shape) is a common problem in roll forming and there are several methods for overcoming this. Where springback is likely to be a problem careful section orientation will allow the use of side rolls to "overbend" a leg.

The sections orientation will be influenced by the preferred vertical centre line. The vertical centre line is a theoretical line whose position relative to the centre of the machine does not change (see Figure 3.2). Where mention is made of the left hand side or right hand side of a section this refers to the position relative to the sections centre line. The vertical centre line is itself often a comprise, the main criteria for choosing the vertical centre line being balancing horizontal forces each side of the guide line, allowing metal movement by forming rather than drawing and choosing a vertical centre line which passes through the deepest part of the section.

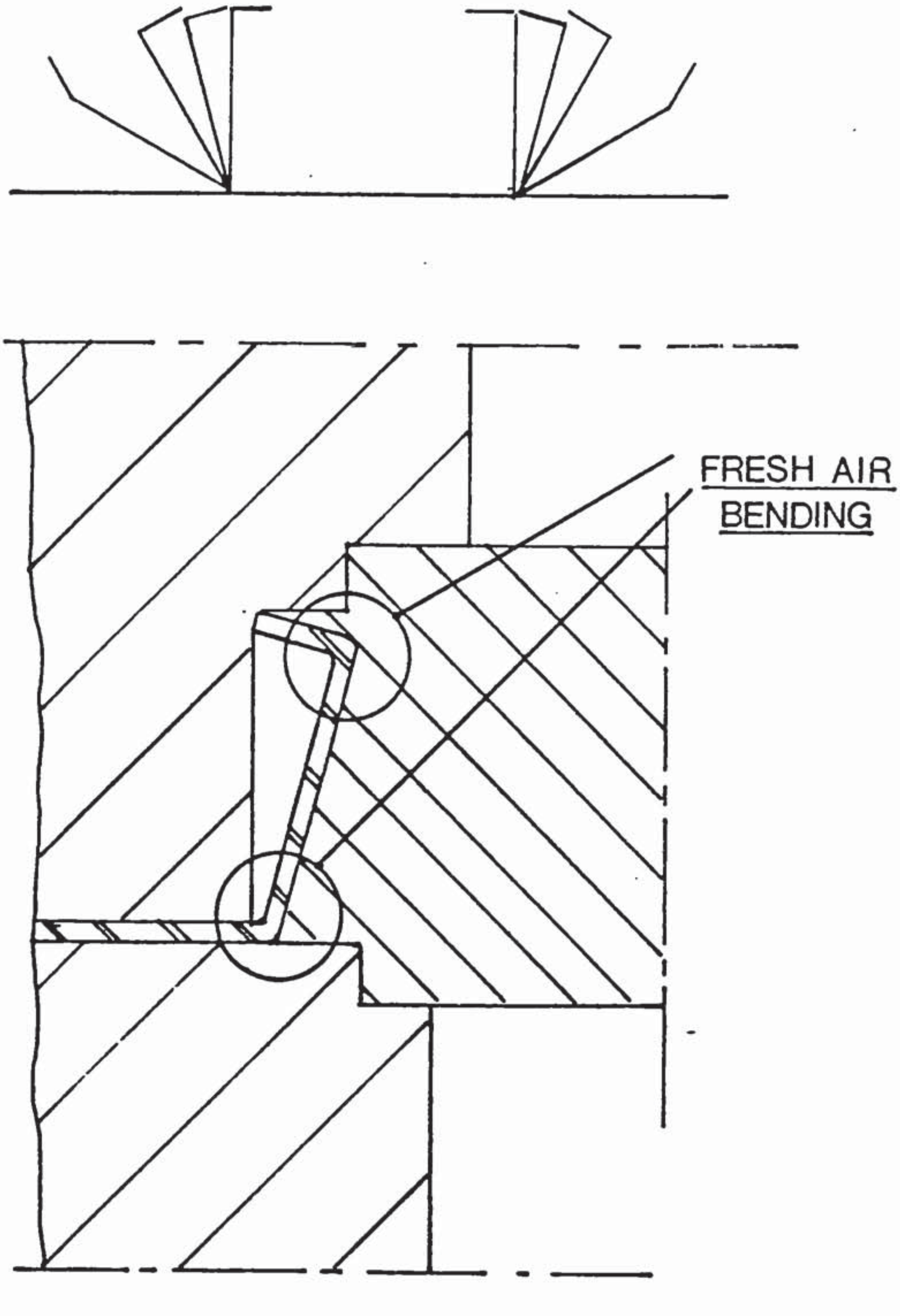


FIGURE 3.1 EXAMPLES OF FRESH AIR BENDING

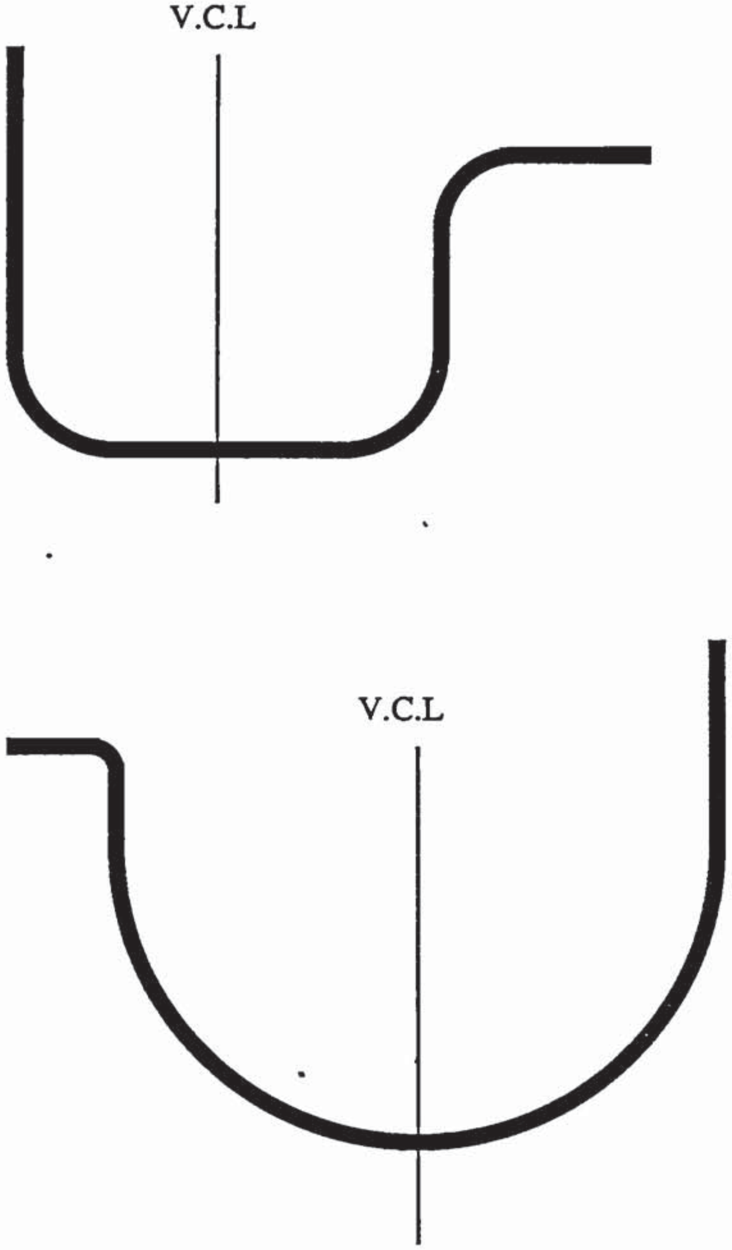


FIGURE 3.2 EXAMPLES OF THE VERTICAL CENTRE LINE

The surface finish of prefinished material can be damaged by careless orientation. The prefinished material should be orientated so as to minimise "rubbing velocity "(the relative roll velocity between opposite surfaces) and also if possible to aid operator inspection. Staining may occur on sections if coolant trapping is possible, this may be minimised by careful orientation of a section.

Auxiliary operations such as notching, piercing, embossing and welding can obviously dictate a section's orientation, cut off tooling should also be considered, since, by careful orientation it may be possible to eliminate additional deburring operations by altering the position of the burr.

The factors mentioned above cannot be considered exhaustive, (merely representative), since any section may produce unique problems and may require a unique solution demanded by equipment, tooling personnel and setting constraints.

3.3.2 SEQUENCING OF BENDS

The order in which the designer chooses to form the bends is termed the sequencing of the bends. In very simple sections such as channels and angles there is no choice in the sequencing (since there is only one bend) in complex sections there is obviously a very large number of possible permutations.

Ideally, designers work from the centre line outwards in sequencing, which would mean that a bend once formed would never be subject to further deformation. However when sequencing bends a designer must consider a large number of, often, conflicting factors. Hence it is often not possible to work from the centre line outwards since often there are good reasons to form by other sequences, for instance to avoid fresh air bending or to reduce metal movement or to avoid excessively large bending moments or to improve the smoothness of the flow of the material.

Fresh air bending refers to bending where only one roll is in contact with the active bend, such as in Figure 3.1, it is sometimes impossible to eliminate fresh air bending in a section but by careful sequencing of bends it is possible to minimise it. Careful sequencing can also reduce the amount of metal movement between passes. Figure 3.3 shows an example where sequencing has been used to reduce the amount of metal movement, however, it is sometimes a mistake to attempt to reduce the amount of metal movement to a minimum by this method.

3.3.3 AMOUNT OF BENDING AT EACH STAGE

Having decided how a section will be orientated and the sequence by which bends will be formed it is necessary to decide how much bending should take place at each stage. Whilst there are a number of techniques to aid the designer in deciding how much forming to perform there is no one generally accepted method.

Many designers have adopted standard sequences of bends for forming legs, for instance the Russian school of roll design recommends the sequence[16]

8° 18° 30° 44° 58° 70° 80° 88° 90°

For forming a leg. Whilst such standards are quick and simple they take no account of sectional properties, material properties or mill properties and cannot be considered ideal.

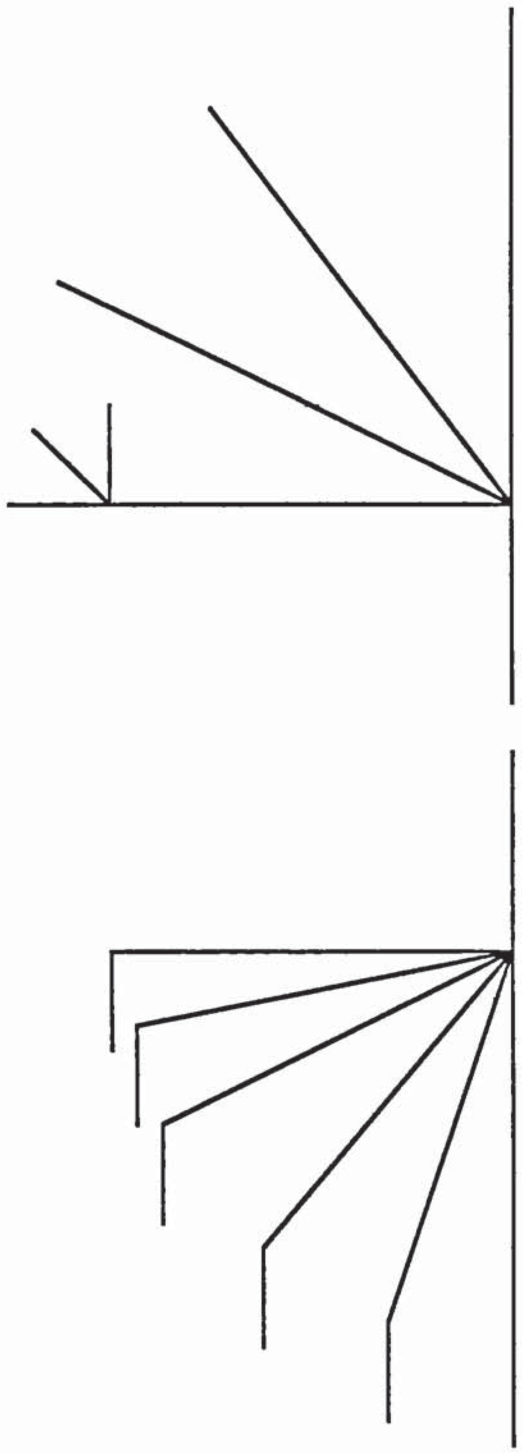


FIGURE 3.3 EXAMPLE OF REDUCED METAL MOVEMENT BY CAREFUL SEQUENCING

The conventional theory for deciding how much bending should take place at each stage is Angel's forming theory[17], which has been empirically derived and states.

$$N = (L/D) * \text{Cot}(\phi)$$

where :

N = Number of stages

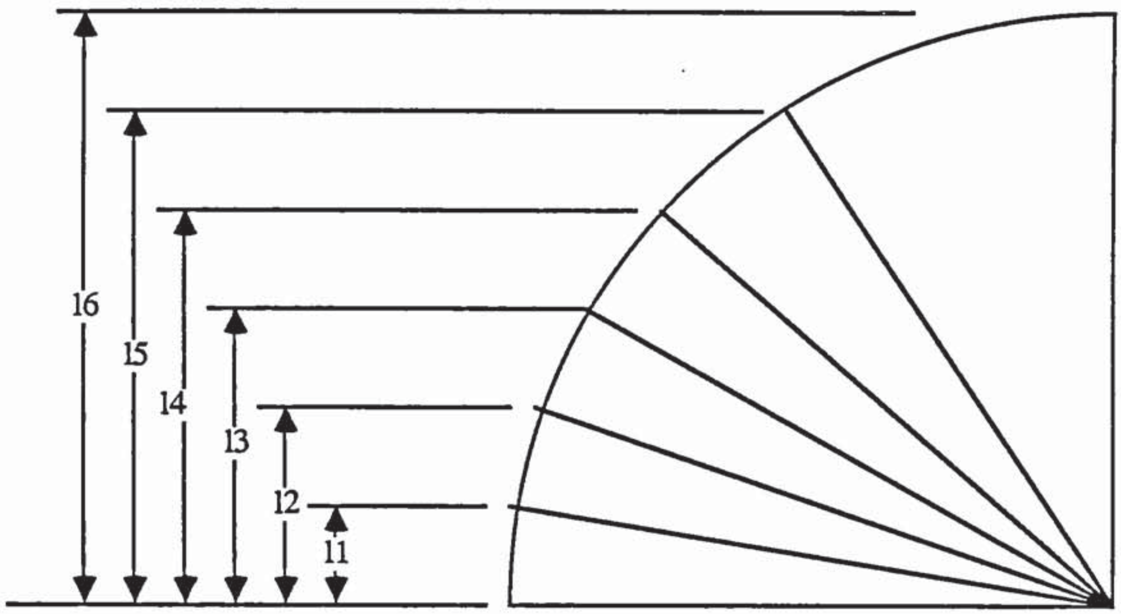
L = Leg length

D = Pass length

and ϕ is some forming angle (commonly $1^{o}25'$)

This is represented diagrammatically in Figure 3.4. The forming angle theory, then, takes one mill property (pass length), one sectional property (leg length) and one material property (the forming angle (which purportedly is a statement of the materials formability)), to determine the number of passes required to form the bend.

It should be noted, however, that several authors have questioned the validity of the forming angle theory, primarily since it infers that as you increase the pass length you can always perform correspondingly more bending, Sarantidis[18] argued that, since, from experimental work he observed that virtually all the forming took place in the region of the rolls the pass length was hence irrelevant. Cadney[19] argued that the forming angle theory took no account of the discontinuous metal movement and also that the experimental work which the theory was based on was probably unrepresentative.



ANGELS FORMING THEORY

(16-15)=(15-14)=(14-13)=(13-12)=(12-11)=11=CONSTANT

WHERE CONSTANT = PASS LENGTH * TAN (FORMING ANGLE)

AND THE FORMING ANGLE IS A STATEMENT OF THE MATERIALS

' FORMABILITY ' (COMMONLY 1 degree 25 minutes)

FIGURE 3.4 ANGELS FORMING THEORY

3.3.4 MEANS OF FORMING BENDS

Having decided on the sequencing and magnitude of the bends it is necessary to think of the means of forming of bends, in general the only parameter within the designers control is the inside radius of the bend (although it is possible to control the shape of the bends also).

The two most common methods of forming bends are the constant inside radius method and the constant element length (Figures 3.5 and 3.6). Each method has its advantages, the constant inside radius method reduces springback and distributes deformation more evenly between passes whereas the constant element length method reduces wear on the rolls and reduces the likelihood of "trapping" of metal.

The designer should obviously decide which method is the most suitable for each job, in practice it seems likely that individual designers use one method or the other and become skilled in minimising that methods disadvantages.

3.4 ROLL DESIGN

Traditionally rolls are manufactured by consulting two items, the template (which will be described in a later section) and the roll drawings. Clearly large portions of the roll profile will be dictated by the flower pattern described earlier, however there are additional features which require the designers consideration at the roll design stage.

In order to form (near) vertical legs and to perform the minimum amount of fresh air bending side rolls may be used, however on many mills where side rolls are used the pass cannot be used to "drive" the metal, therefore, whilst side rolls are often indispensible, the designer must be very careful when deciding when and how to use side rolls.

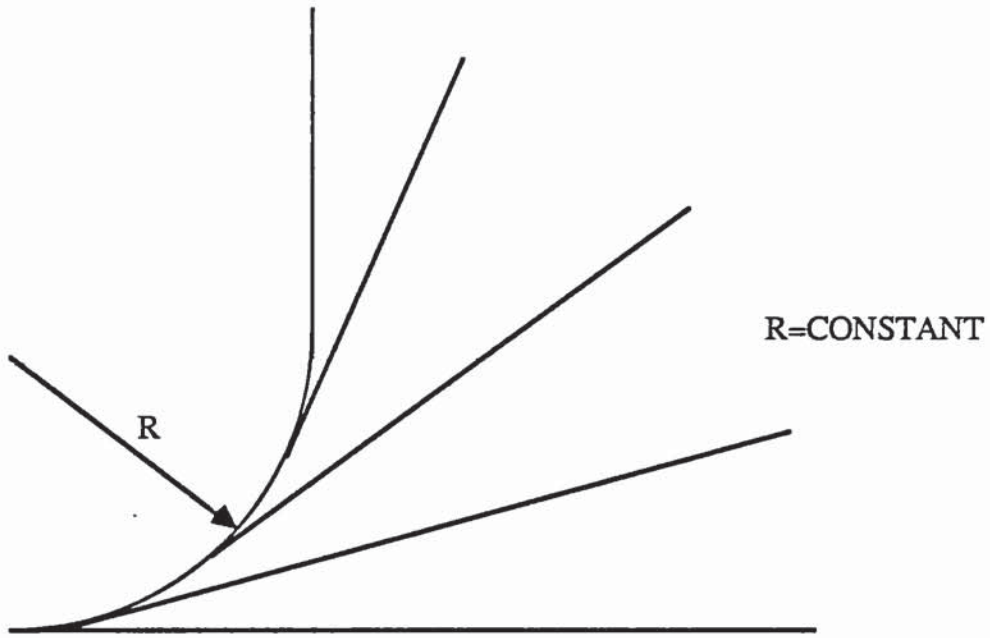


FIGURE 3.5 CONSTANT INSIDE RADIUS METHOD
OF FORMING BENDS

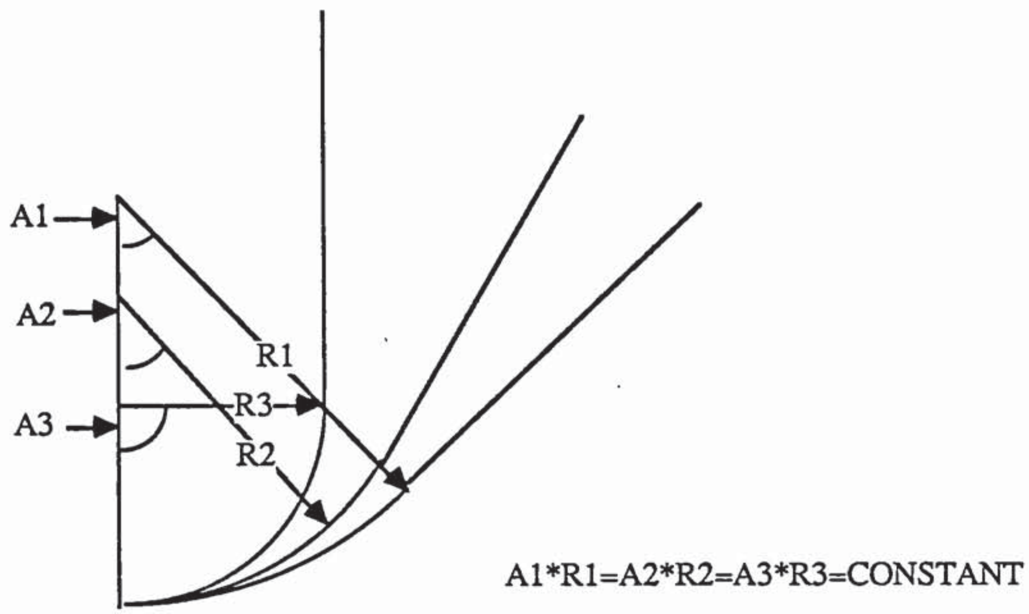


FIGURE 3.6 CONSTANT ELEMENT LENGTH METHOD
OF FORMING BENDS

In order that "drive" will always occur the distance between the driving surfaces must be less than or equal to the minimum permissible metal thickness (obtained from the relevant British Standards). Since it is undesirable to have contact on non drive surfaces the distance between non drive surfaces must be adjusted to greater than or equal to the maximum metal thickness (again obtained from the relevant British Standard).

The roll drawing defines the gating, where the gating (or extension countours) lock the rolls together. The type and size of gating depends on the scale and orientation of the section but in general is not critical to the forming of the section.

The diameter of each roll must also be decided at this stage, the radius of the centre of the bottom roll is referred to as the "pass height" whilst the radius of the bottom roll plus the strip thickness plus the radius of the top roll is referred to as the roll centre to centre distance. Choosing a larger roll diameter will often result in the deformation being more evenly distributed between passes and reduces the differential surface velocity between different parts of deep sections. However larger diameter rolls are more expensive to manufacture and may result in production and setting difficulties. By altering the pass heights it is possible to create "uphill or "downhill" on a section, some designers like to arrange the pass heights so as to keep the vertical component of the sections centroid constant whilst others prefer constant pass heights.

Roll design drawings can be extremely complex and densely dimensioned containing all of the information required to produce the component or more commonly, can just contain the information which is required together with the wire template to produce the rolls.

3.5 WIRE TEMPLATE PRODUCTION

Having finalised the form roll design the next stage is to determine the method of transferring this information to the machinist in order to produce the rolls. One of the methods of achieving this with form rolls is by producing a wire template to accompany the roll drawings.

These wire templates are sections of the strip which have been bent up to represent the strip shape at each stage in the forming process. Since the shape may be very intricate (particularly on small complex sections), and the work is necessarily done by hand, it can be imagined that a significant level of skill is required in forming these templates.

The initial stage is to draw the "ten to ones", that is to draw each template out at a scale of 10.1. This drawing is placed on a shadowgraph and the wire is then bent up using pliers to the shape shown on the shadowgraph. The template drawings can also be used as quality control aids so that a strip can be cut out from the section and checked on the shadowgraph against the template drawings for geometric accuracy.

3.6 CONVENTIONAL ROLL MANUFACTURE

Using conventional machines tools there are several methods for producing rolls.

(I) One method adopted by some companies is to produce a detailed working drawing of the roll and give this to the machinist. Such drawings are often extremely complex and demand considerable skill in interpreting the drawing and machining the roll. Also, this method is prone to errors since it is difficult to check the rolls geometry and thus it is rarely used where rolls are being continuously produced.

(II) Another method of manufacturing rolls is to mill a solid brass template which then defines the entire profile of the roll. This template can then be used in conjunction with a copy lathe to manufacture the roll. Whilst this method is more reliable than that above, manufacturing the brass template is both expensive and time consuming, the method also requires the availability of a copy lathe.

(III) A commonly adopted compromise is to use a wire template (detailed in section 3.5) with a simplified roll drawing (which defines that information which is not contained in the wire template). This method still relies heavily on the machinists skill although the wire template can be used for checking the profile.

3.7 LIMITATIONS OF CONVENTIONAL DESIGN AND MANUFACTURE OF FORM ROLLS

By considering the previous sections it will be seen that central to the form roll production process is the form roll design and in particular the flower pattern design.

Surrounding this, however, are a large number of tasks which, although relatively routine in nature are time consuming and a possible source of error. These include large amounts of calculation, section drawing production, flower pattern drawing production, wire template production, template drawing production and roll drawing production. Additionally, whatever the quality of the design, the quality and accuracy of the form rolls is heavily dependent on the machinists skill giving another potential source of error.

The situation where the designer spends a large proportion of his time on tasks which are peripheral to the design process is not unique to form roll design but common to almost all design processes. One method commonly used to alleviate this problem is to use computer aided design (CAD) techniques. Similarly the situation where the manufacture of an article is heavily dependent on the machinists skill is not unique to form roll manufacture but is common to the manufacture of many components and especially tooling. One technique which is increasingly applied is using numerical control (NC) machinery.

By analysing conventional design and manufacture of form rolls, then, one can see considerable advantages in the application of the computer. The CAD/CAM system which has been developed for the production of form rolls and the advantages which have resulted will be detailed in the following chapters.

CHAPTER 4

COMPUTER AIDED GEOMETRIC DESIGN OF FORM ROLLS

4.1 INTRODUCTION

In general, having decided to implement CAD/CAM techniques there are two distinct paths which can be taken. Firstly a 'turnkey' system may be purchased from a software vendor (there being presently at least 30 commercially available drafting packages and the advantages of a purchased package are robustness and instant availability). The alternative is to develop ones own package, the advantages of this method are that software can be tailor made for specific needs and that the end user can advise on software design with regards to its useability. Since form roll design is such a clearly defined and idiosyncratic progress the most logical solution was to write a tailor made package.

The programming language used was FORTRAN 77 which combines transportability with the ability to easily process large numbers of numerical calculations. The Gino-F[20] graphics package was used since it features a wide range of graphical facilities and is also easily transportable since drivers are available for a wide range of devices.

Several other organisations have recognised the need for CAD/CAM systems dedicated to form roll design and manufacture. For instance the system developed by MTIRA[21] in Britan, the system developed by Roll data[22] in America , the system developed by Industrie Secco[23] in Italy,the system developed by Delta engineering[24] in Canada and the system developed by John Lysaght[25] in Australia. Each system has features which are not present in the other systems, this does not indicate shortcomings in any system merely the individual nature by which different organisations design and manufacture form rolls.

The system which has been developed at Aston is shown diagramatically in Figure 4.1 and is probably most clearly illustrated by detailing each program individually under the two general headings, computer aided design and computer aided manufacture.

4.2 COMPUTER AIDED DESIGN SOFTWARE

Figure 4.1 details the programs which collectively form the computer aided design software, namely:

(1) Finished section software

(2) Flower pattern software

(3) Template Software

(4) Roll design software

(5) Roll editor software

Each of these programs is described in a separate section. To illustrate the use of the system each section is detailed with system produced drawings. These figures all belong to a single "job". The data files produced by this job and the terminal session which input the job are documented in Appendix A.

The finished section, flower pattern and roll design programs all run in two modes. Firstly the programs can be run by keyboard input and secondly the program can be run by using the data file which is created when the programs are run in the first mode.

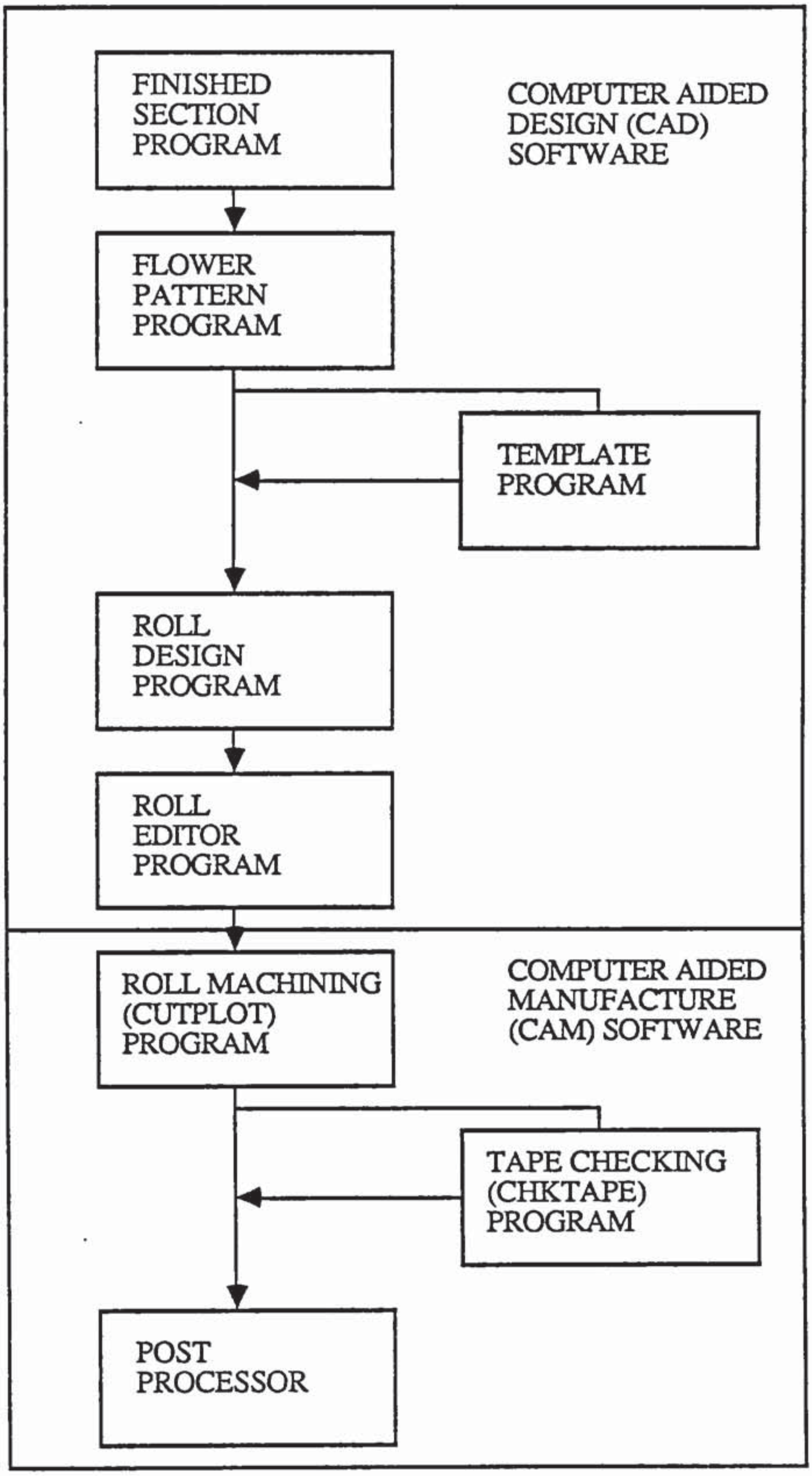


FIGURE 4.1 CAD/CAM SYSTEM SOFTWARE

4.3 FINISHED SECTION SOFTWARE

The purpose of the finished section program is to fully define the finished section, to produce the finished section drawing and to perform the strip length calculations.

Initially, the sections thickness must be defined, which is uniform over the section. Secondly the sections shape must be defined, the definition may start from either of the two ends or from the centre of the section. Since, in the vast majority of cases, the sections shape is constructed from circular and linear elements the section definition consists of linear and circular elements. The pertinent information, for defining the section, is length (for linear elements) or angle and inside radius (for circular elements). The convention used for bending of circular elements is positive for upward bending and negative for downward bending.

To produce the finished section drawing it is necessary to define paper size, section scaling and the title block information. The full title block options are detailed in table 4.1. A typical finished section drawing is shown in Figure 4.2.

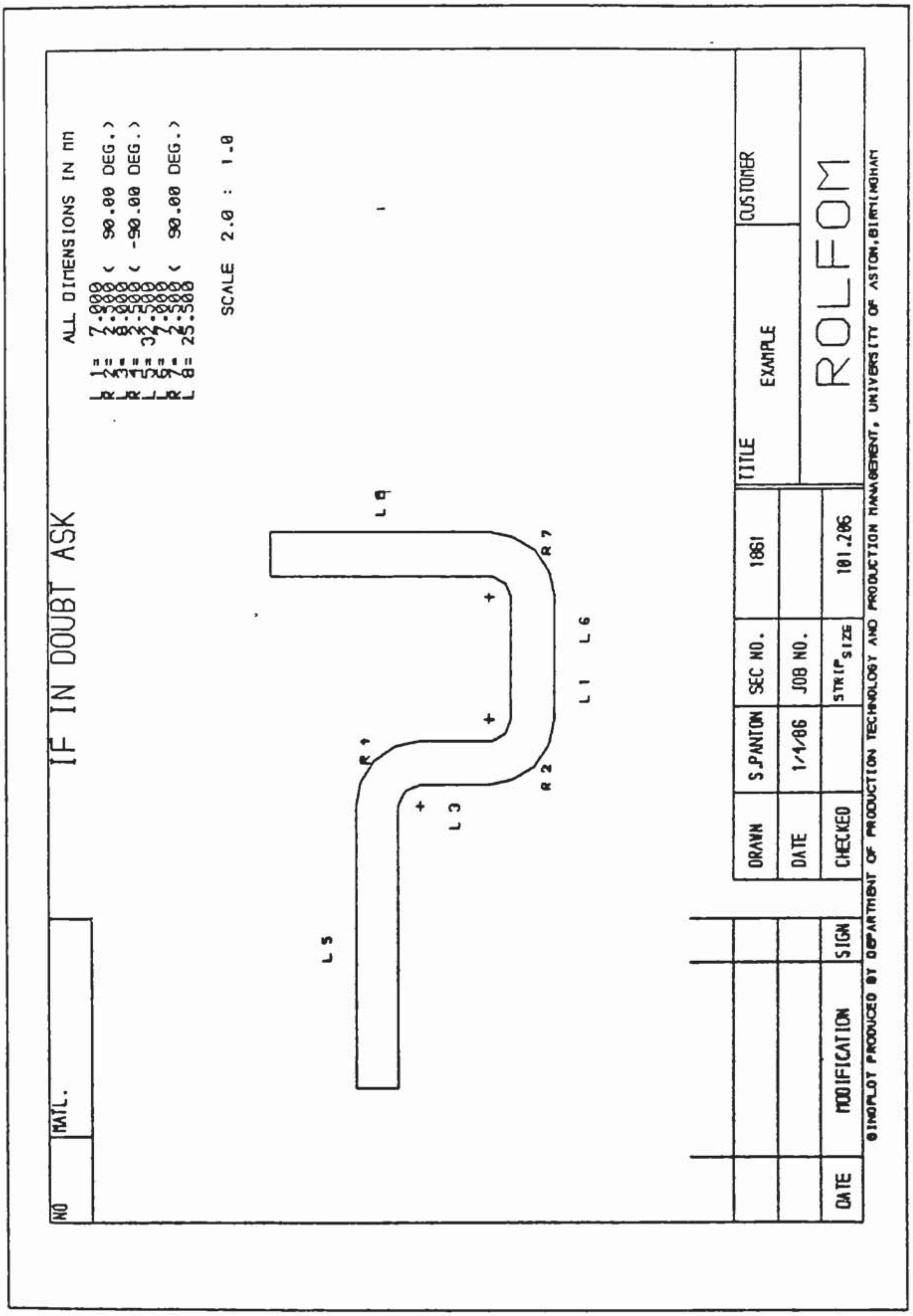


FIGURE 4.2 FINISHED SECTION DRAWING

NUMBER	DESCRIPTION	MAXIMUM NO OF CHARACTERS
1	TITLE	29
2	CUSTOMER	19
3	SECTION NUMBER	14
4	JOB NUMBER	14
5	STRIP SIZE	DETERMINED INTERNALLY
6	DRAWN	9
7	DATE	9
8	CHECKED BY	9
9	NUMBER	9
10	MATERIAL	24

TABLE 4.1 TITLE BLOCK OPTIONS

A feature of the finished section software is the automatic strip length calculation. It is important to calculate the strip length accurately to ensure geometric accuracy in the section. The strip length (or strip width or strip size) is obviously the sum of the individual element strip lengths. For linear elements the strip length is the same as the element length, since the linear elements are nominally unstrained during forming.

For circular elements the strip length is calculated as the product of the angle of bending and the radius to some neutral axis, referred to as the mean radius.

i.e. $R_m = R + kt$ - (1)

where: Rm = mean radius

R = inside radius

k = some constant (the bend factor)

t = thickness

There are several methods of determining the bend factor(k). Kaltprofile[26] recommends the factors determination according to table 4.2.

R/t	>0.65	>1.0	>1.5	>2.4	>3.8
K	0.30	0.35	0.40	0.45	0.50

TABLE 4.2 BEND FACTORS ACCORDING TO KALTPROFILE

According to BS 2994 the factors should be defined by the following method.

$k = 0.5\, t_r$ - (2)

where $t_r = (R + k't)\, t / (R + 0.5\, t)$ - (3)

where k' = 0.3 where R/t > 1

k' = 0.35 where R/t > 1.5

The American Society of Mechanical Engineers[27] suggest the factor should be be 0.4475, irrespective of the radius. The American Society of Metals[28] suggest that the factor should be determined by a method which is summarised in table 4.3. However, whilst it is certainly true that material properties do effect the strip length the distinction between normal metals and less formable metals is an arbitary one.

R/t	0		0 - 2	>2
K	NORMAL METAL	0.33	0.33	0.5
	LESS FORMABLE METAL	0.5		

TABLE 4.3 BEND FACTORS ACCORDING TO THE AMERICAN SOCIETY OF METALS

In practice, from practical observation, it would appear that most companies adopt some form of personalised empiricism when calculating circular strip lengths and that most consider only the radius to thickness ratio. The empiricism conventionally adopted by Hadley Industries is based on the angle of bending. Since practical observation has shown that bends of smaller angle require a smaller bend factor the bend factors shown in table 4.4 were used.

ANGLE OF BEND (DEGREES)	0 - 80	80 - 100	>100
K	0.3	0.4	0.5

TABLE 4.4 BEND FACTORS ACCORDING TO HADLEY INDUSTRIES

Apart from the above empirical methods, there is also a seemingly, little used theoretical method by Hill[29] for calculating the neutral axis of a bent sheet, which, by considering equilbruim of an element on the neutral axis derives the expression.

$$R_m = \sqrt{(R (R + t))} \qquad - (4)$$

From practical experience it is known that the strip length is dependent on the radius to thickness value, the angle of bend and also the material properties of the metal. The application of the computer allowed the development of a strip length calculation which was more sophisticated than the conventional techniques.

The program interprets each circular element and chooses a factor from a two-dimensional array dependent on the radius, thickness and bend angle. Such an array is detailed in table 4.5, these arrays are contained in data files which have been constructed using the expertise of a group of designers. A separate data file can be created for each group of metals showing distinct properties. Thus the program calculates the strip length on the basis of radius, thickness, angle of bend and type of material. Additionally, since the information is contained in data files it can be readily updated. Thus by comparing calculated and required strip lengths it is possible to continually improve the accuracy of calculation by improving the information stored in the data files.

BEND (degrees) \ R / t	<0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5	2.5 - 3.0	3.0 - 4.0	> 4.0
.<20	0.300	0.300	0.330	0.380	0.420	0.450	0.500	0.500
20-40	0.300	0.300	0.330	0.380	0.420	0.450	0.500	0.500
40-60	0.350	0.350	0.380	0.400	0.430	0.450	0.500	0.500
60-80	0.400	0.400	0.430	0.450	0.450	0.450	0.500	0.500
80-100	0.400	0.400	0.430	0.480	0.500	0.500	0.500	0.500
100-120	0.450	0.450	0.500	0.500	0.500	0.500	0.530	0.530
120-140	0.500	0.500	0.500	0.500	0.500	0.530	0.530	0.550
140-160	0.500	0.500	0.500	0.500	0.530	0.530	0.550	0.550
>160	0.500	0.500	0.500	0.530	0.530	0.530	0.550	0.550

TABLE 4.5 BEND FACTOR ARRAY

4.4 FLOWER PATTERN SOFTWARE

The flower pattern design is central to roll production ,as such it was detailed in an earlier section (section 3.3). The purpose of the flower pattern software is to facilitate the design and drafting of the flower pattern. Features of the software, intended to achieve this include automatic drawing production, a composite element length option and a radii sharpening facility.

Initially the flower pattern must be defined, this is achieved by nominating the elements to be bent at each stage, the amount of bending to take place at each stage and the manner in which the element is to be formed. This information is combined with an intermediate data file created by running the finished section program; to fully define the flower pattern.

The program automatically produces two drawings of the flower pattern, the first with the individual stages on a separate origin (Figure 4.3) and the second with each stage on a separate origin (Figure 4.4). This gives the designer a reasonable visualisation of his flower pattern design. The data file produced (the F file) is listed in Appendix A.

The designer has the option to split any circular element into three composite elements (Figure 4.5) which allows the designer to infinitely vary the manner in which the bend is formed. The designer may also choose the constant element length option or the automatic percentage element length option, each of which determine the composite element lengths automatically. The constant element method is described in section 3.3 whilst the automatic percentage composite element option is fundamentally different from the other two and as such is treated in more detail.

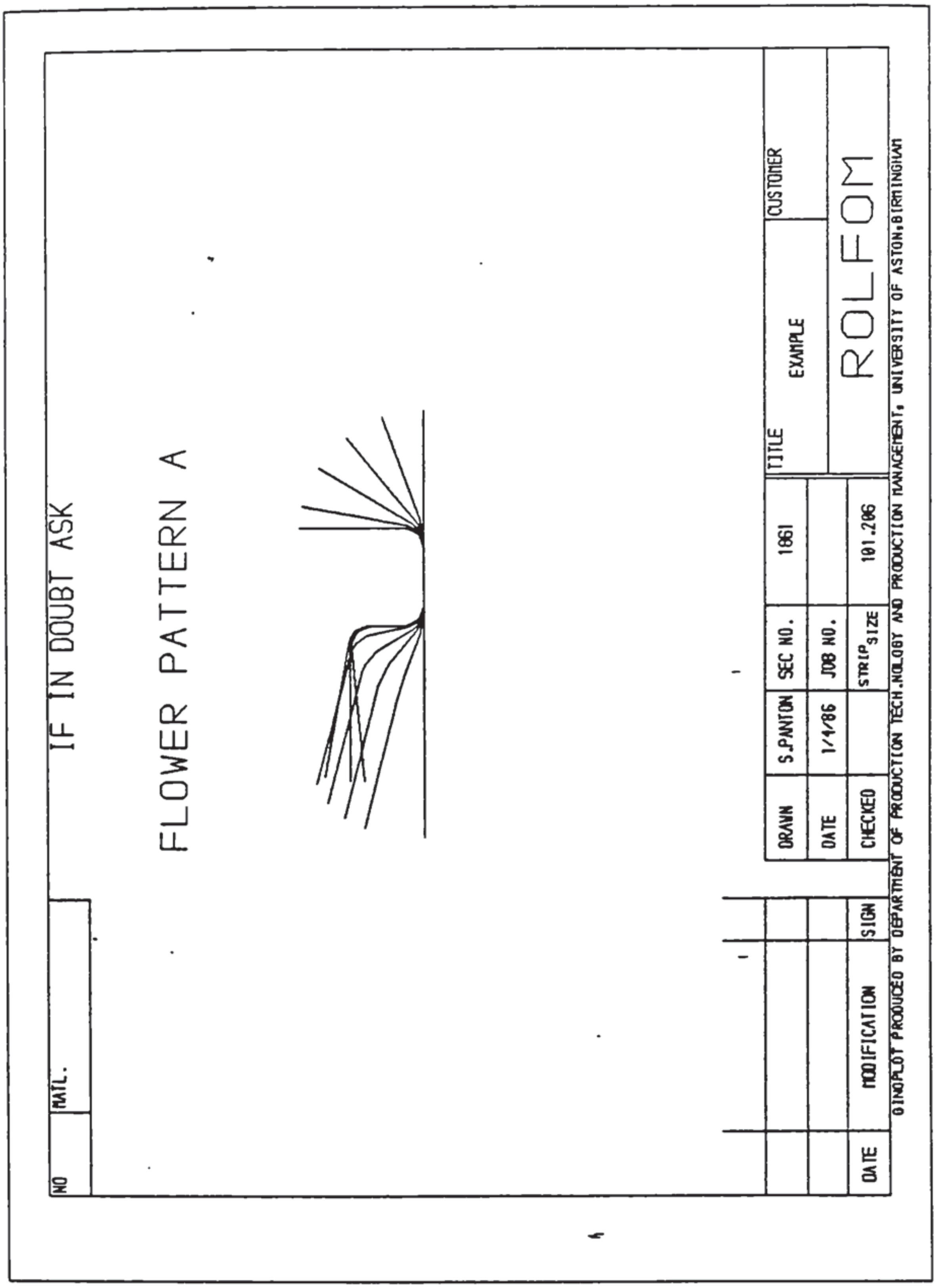


FIGURE 4.3 FLOWER PATTERN DRAWING

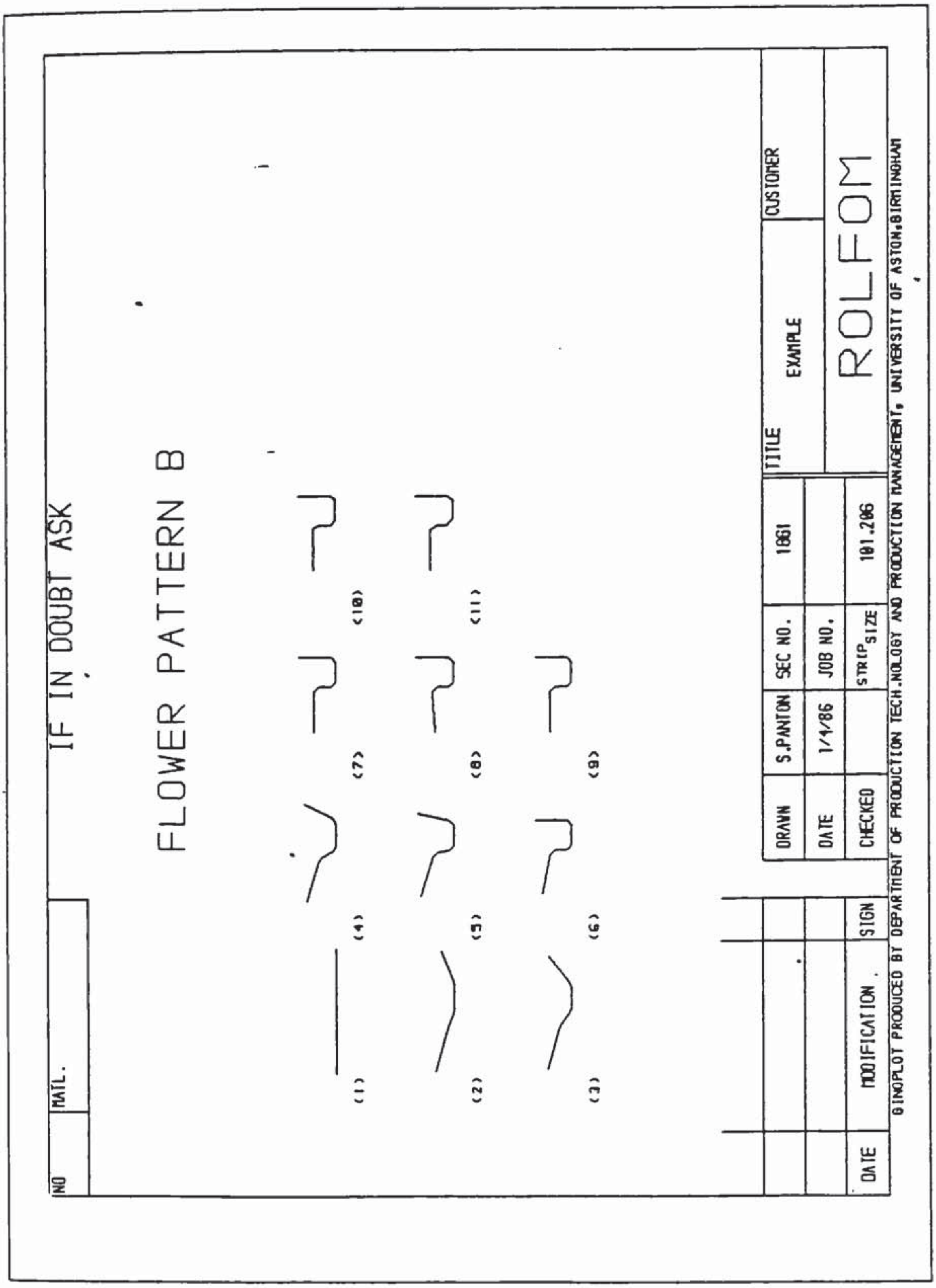
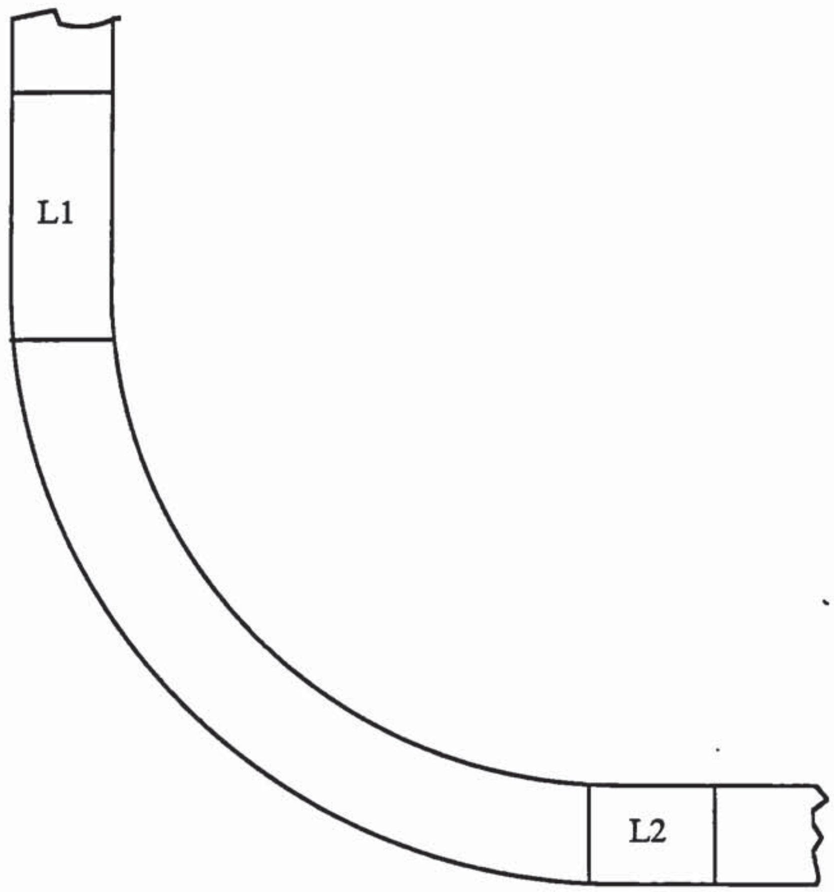


FIGURE 4.4 FLOWER PATTERN DRAWING B



THE COMPOSITE ELEMENT LENGTH OPTION ALLOWS THE DESIGNER TO DIVIDE THE BEND INTO THREE SECTIONS THE LEADING LINEAR ELEMENT (L1), THE BEND ITSELF AND THE TRAILING LINEAR ELEMENT (L2).

FIGURE 4.5 COMPOSITE ELEMENT LENGTH

As was described previously, the means of forming bends is an important part of the flower pattern design process. To recap, the principal methods of forming are the constant element length method and the constant inside radius method. The principal reason for using the constant inside radius method rather than the constant element length method is that the former method reduces the materials tendency to 'springback' to its original shape. The automatic percentage composite element length option takes as its basis the premise that springback only becomes problematical above a certain permissible level (expressed as a percentage of the final bend angle) and that, since larger radii of bending give distinct practical advantages, the radius of bending should be maximised until either the maximum permissible springback level or the condition of constant element length is reached. The springback level is estimated by Gardiners method which is detailed in section 6.6.

The automatic percentage composite element length option firstly inputs material properties, yield stress and Youngs modulus and also the maximum permissible springback level (as a percentage). For each active bend the radius which would give a theoretical springback level equal to the maximum permissible, springback level is estimated. There are then three possibilities.

1. The radius is smaller than the final inside radius, in which case the composite element lengths are apportioned so as to make the radius equal to the final inside radius (i.e. using a constant inside radius method). At the same time a warning is issued to the screen that the springback cannot be maintained within the permissible level by varying the radius alone. Additionally, the estimated springback with the minimum inside radius is displayed on the screen thus giving an indication of the overbending required.

2. The radius is greater than the final radius but less than the radius which gives a constant element length. In this case the percentage composite element lengths are

adjusted until the radius is that which gives the maximum permissible springback.

3. The radius is greater than the radius which gives a constant element length, in which case all of the element is apportioned to the bend element, (i.e. a constant element length method is adopted).

Having determined the composite element lengths by the method above, the designer is given the option of editing any of the percentages, thus again allowing maximum flexibility.

Since there are often advantages associated with using a smaller radius of bending, namely, reduced springback and a more even distribution of bending throughout the pass, a radii sharpening option is included in the software. When this option is switched on the radii are reduced by thirty percent of their original values. This option is redundant if the automatic percentage composite element length option is used.

In general, then, the flower pattern software has been constructed to allow the designer the same flexibility as conventional methods but by inputting only a very limited amount of information, thus requiring much reduced effort. The designer has greater flexibility than with conventional methods, since, it is simple to change a design by editing the flower pattern data file thus allowing alternative designs to be considered and the most suitable chosen.

4.5 TEMPLATE SOFTWARE

Wire template production is an important feature in the conventional design and manufacture of form rolls and as such was detailed in section 3.5. Whilst by using N.C machines the need for the wire template has been reduced; in order to retain the maximum flexibility the CAD/CAM system includes software to aid the production of wire templates.

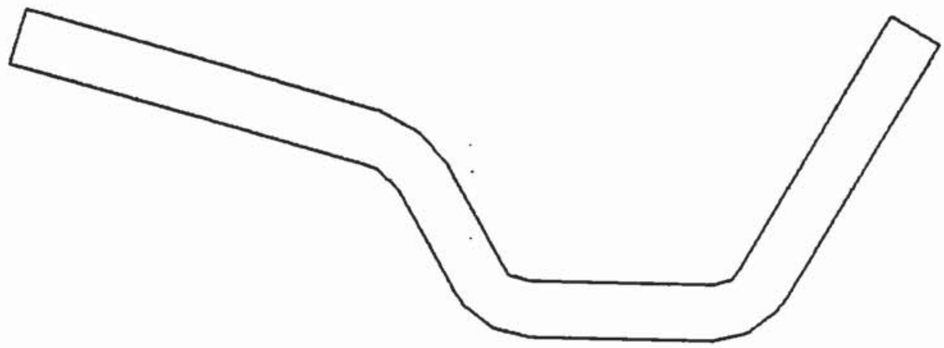
This facility allows templates to be produced for quality control purposes, or if the N.C Lathe is unavailable then it allows rolls to be turned on conventional lathes.

Using conventional techniques wire template production is a time consuming process requiring a high degree of skill. Whilst the process of bending templates will, almost certainly never be automated the 10.1 drawing production can relatively easily be automated, thus considerably reducing the time and effort required in producing the wire templates.

The template software combines the intermediate data file created by the section program with the data file created by the flower pattern program and plots the strip shape at each stage at a scale of 10:1, to produce the template drawings. The template drawings reproduce those features such as radii sharpening and composite element lengths which were defined in the flower pattern drawing, thus producing the exact shape. Additionally as the template drawings are produced the program produces a data file which numerically describes the template and is further used in the wire frame, side and plan views, an example of this file is listed in Appendix A. A template plot is detailed in Figure 4.6.

4.6 ROLL DESIGN SOFTWARE

The various types of form roll and their features are described in section 2.2.1, also, the conventional design of form rolls is detailed in chapter 3. The purpose of the roll design program is to define and draft the form rolls and to quantify the roll profile into a data file suitable for further processing into a N.C tape file. The input to the program consists of the intermediate data file produced by the finished section program, the flower pattern data file and the further data which is required to fully define the roll. This additional data is termed the R-file and an example is given in Appendix A.



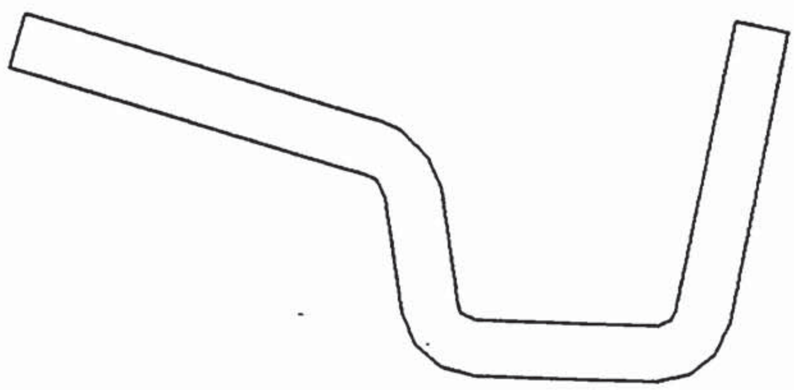


FIGURE 4.6 TEMPLATE DRAWINGS

Figure 4.7 gives an example of a roll drawing produced by the system, (the second stage of the roll design described in Appendix A), Figure 4.8 gives an example of a roll drawing including side rolls, (the fifth stage of the roll design detailed in Appendix A).

Clearly, large portions of the roll profile are defined by the template contour. However, there are occasions (for example Figure 4.9) where sections of the template contour are inaccessible to the rolls and a vertical linear element is automatically inserted into the roll profile. The roll profile is "split" between top and bottom rolls at the points on the left hand and right hand side of the template which are furthest, horizontally from the section centre.

The roll design input can be split into five main groups.

(I) Pass height and roll centre to centre distance

(II) Strip tolerance

(III) Pinch difference clearance definition

(IV) Side roll definition

(V) Extension contour (gate) definition.

4.6.1 PASS HEIGHT AND ROLL CENTRE TO CENTRE DISTANCE DEFINITION

The pass height and the centre to centre distance for a pair of rolls was previously defined in section 3.4. The designer has the option, with the system, of choosing a constant value for the pass height and centre to centre distances or of choosing separate values for each pass along the mill.

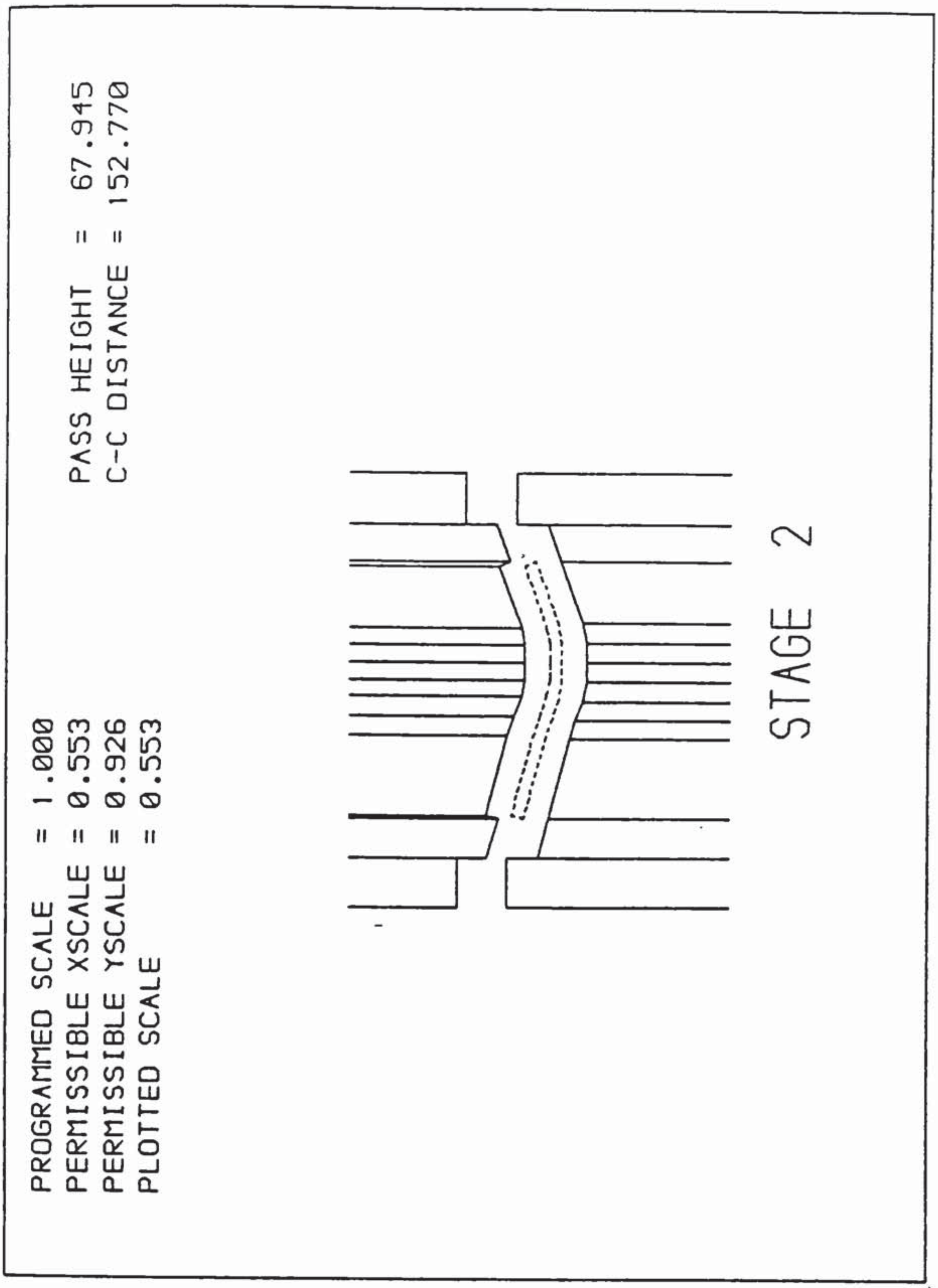


FIGURE 4.7 ROLL DRAWING TOP AND BOTTOM ROLLS

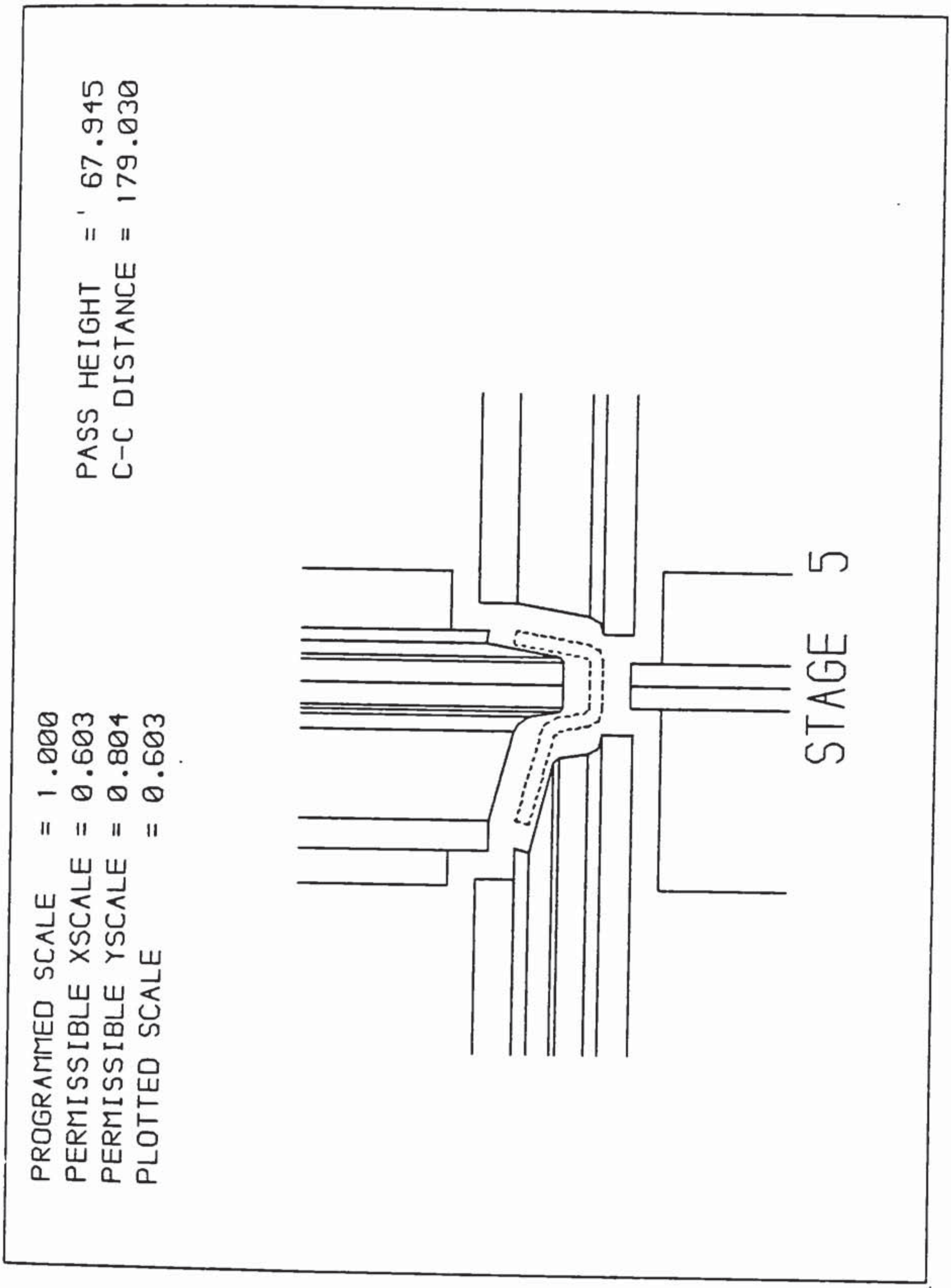


FIGURE 4.8 ROLL DRAWING TOP,BOTTOM AND SIDE ROLLS

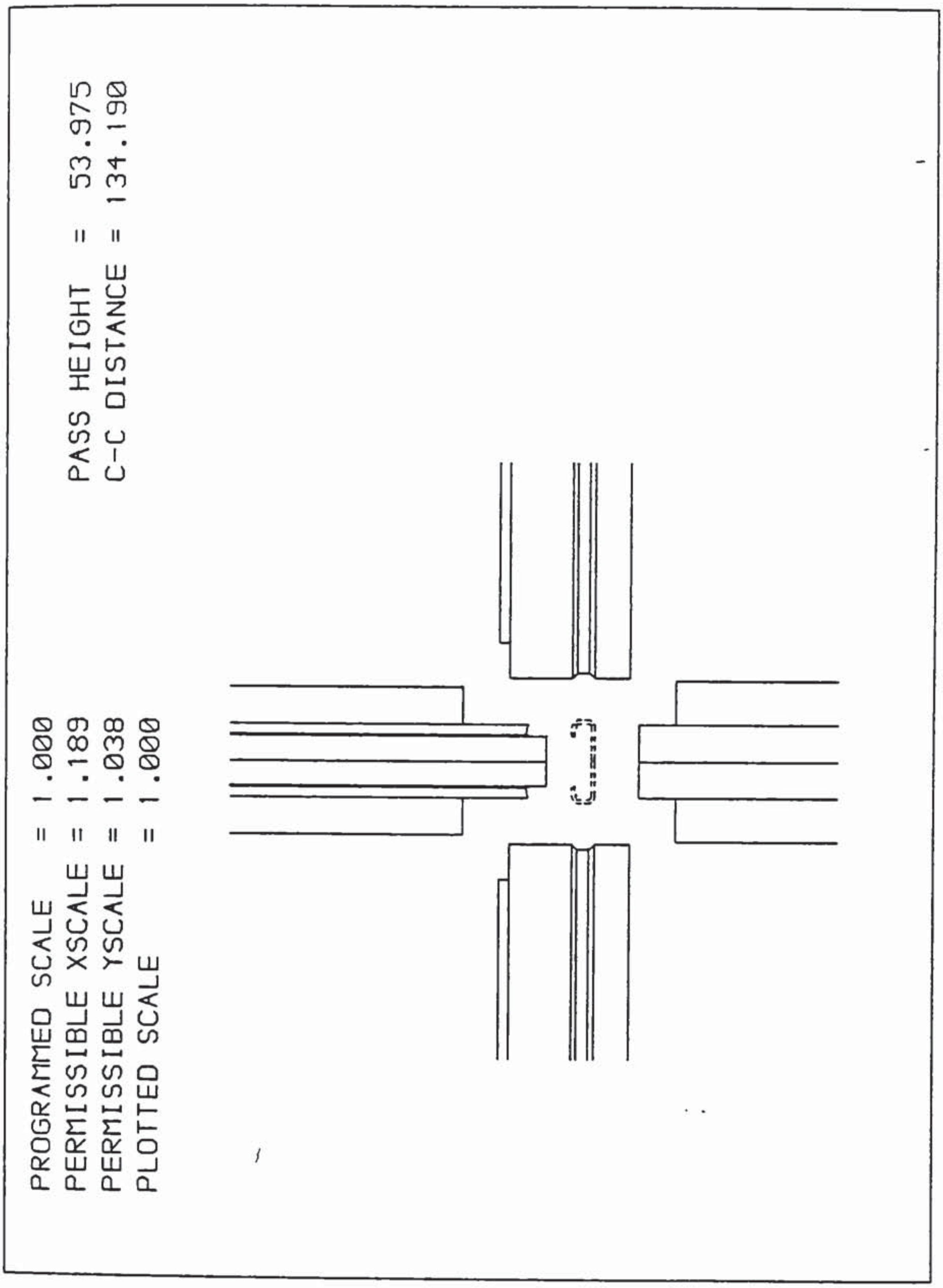


FIGURE 4.9 ROLL DRAWING WITH MODIFIED CONTOUR

4.6.2 <u>STRIP TOLERANCE DEFINITION</u>

Whilst the roll profile has to be based on a nominal strip size, in practice the strip size will be toleranced. In addition, the strip will often have a tendency to move to one side of the roll gap during rolling. Because of this the length of the last template element must be increased (by the strip tolerance) to allow for these features. The designer chooses values for the left hand and right hand tolerances and again has the option of choosing constant values for the tolerances or choosing separate values for each pass.

4.6.3 <u>PINCH DIFFERENCE / CLEARANCE DEFINITION</u>

The pinch difference option is the means by which the gap between opposing surfaces of the roll is controlled. The gap must be varied, since, the roll radius varies over the profile and thus the surface speed varies over the roll profile. If all surfaces were in firm contact with the strip the result would be to distort the section.

Normal roll design practice would be to select a single surface (the drive surface) which both rolls are in contact with and have at most one roll in contact with the remainder of the profile (thus creating clearance). The drive surface is commonly chosen as being the deepest part of the section parallel to the roll axes (whenever this is possible).

The pinch difference is the perpendicular distance between the drive surfaces, pinch difference values can be calculated by consulting tables of empirically derived values or from experience. Clearance values are normally such that if the material is at its maximum tolerance then there will still be clearance. As before the designer can choose one pair of drive and clearance values for all of the passes or can choose individual drive and clearance values for each pass.

4.6.4 SIDE ROLL DEFINITION

Side rolls are rolls with their axes vertical used for forming vertical or near vertical legs and as such were previously described in section 2.2.1. It is important that any CAD/CAM system for form rolls allows the designer the option of choosing side rolls for particular stages and to define these side rolls. In order to fully define a side roll it is necessary to define the roll diameter and the section of the template profile on which the side roll acts. The side roll diameter is calculated by defining the distance from the centre of the template to the side roll axis. Again the designer can nominate a single pair of values for all of the stages or can define the side roll diameters at each stage independently.

4.6.5 EXTENSION CONTOUR (GATE) DEFINITION

Gates (or extension contours) are those parts of the roll profile which play no part in forming but serve to lock the roll sets together. There are 3 possible types of gates (shown in Figure 4.10), each of which is defined by 4 dimensions. When using the extension contour option the designer first defines the type and dimensions of those gates he will use. The designer then selects that gate which he wishes to use at each stage from those previously defined. When side rolls are used it is necessary to select two gates per side, with top and bottom rolls it is necessary to select one gate per side.

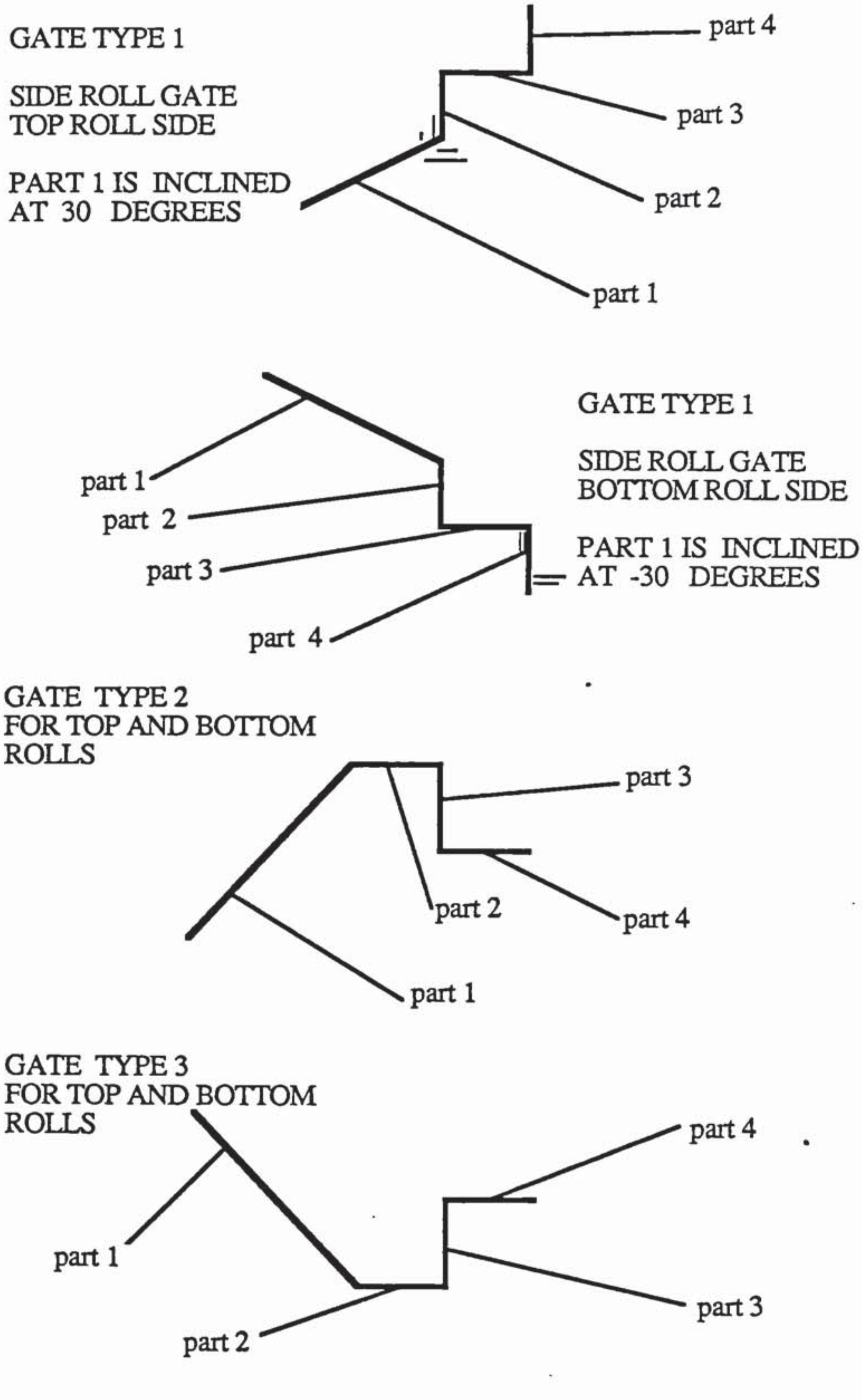


FIGURE 4.10 EXAMPLES OF ROLL GATING

4.7 ROLL EDITOR PROGRAM

The roll design program (described in section 4.6) produces a data file which defines the nominal geometry of each roll. Whilst the general shape of the rolls will be correct, it is desirable that the designer has the freedom to make whatever minor modifications he requires to this geometry. As an example it is common to replace sharp corners with blend radii for ease of manufacture. To perform this and other random modifications the roll editor program has been developed and as such it is a powerful tool giving the designer maximum freedom in defining the ultimate roll shape.

The roll editor program takes the roll data file as its input and produces an edited roll file for each roll profile. The user is prompted by a menu and has the following options.

(1) Inserting a new element (linear or circular) to the profile.
(2) Replacing an existing element by a new element.
(3) Deleting an existing element.
(4) Modifying a corner by adding a blend radius.
(5) Enlarging a section of the profile on the screen.

When the insert or replace option are used the designer must obviously define an element which may be either linear or circular. Clearly, there are many ways that lines and circles can be defined, the roll editor program allows the following:

For linear elements:

(1) By defining two points
(2) By defining a point and an angle
(3) By defining a point and a given line which is parallel

For circular elements:

(1) By defining the circle centre and the radius

(2) By defining the circle centre and a point which the circle passes through

(3) By translating the centre of an existing circle

(4) By defining the radius and two tangential lines

When the delete option is used the two adjacent elements must obviously intersect. Option 4, the corner modification option is a special case of the insertion option. With it one can insert either a blending radius (by inputting a radius valve) or a chamfer (by inputting the depth of chamfer) between two linear elements.

The roll editor runs in an interactive mode, where modifications are made the user can obtain the edited roll profile on the screen immediately after. However, whilst this is obviously a great assistance, many of the details of the roll profile are too small to be reasonably studied, thus the designer is given the option of enlarging a certain area of the profile to fill the entire screen. To use this option the designer uses the cursor to nominate two points on the screen and these identify two opposite corners of a box, this box is then enlarged until it fills the whole screen. Figure 4.11 gives an example of a edited roll drawing.

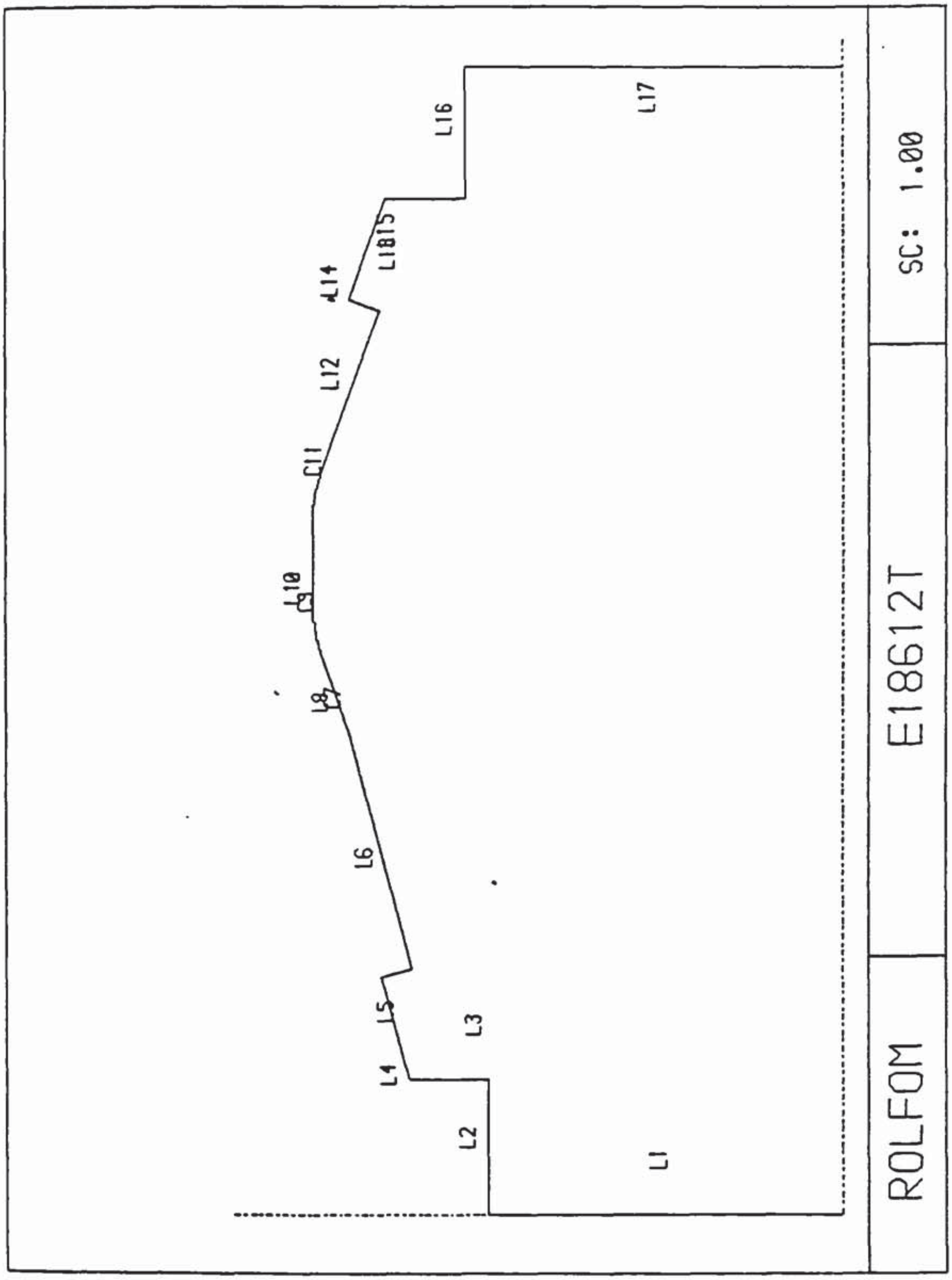


FIGURE 4.11 ROLL EDITOR DRAWING

CHAPTER 5

COMPUTER AIDED MANUFACTURE SOFTWARE

5.1 INTRODUCTION

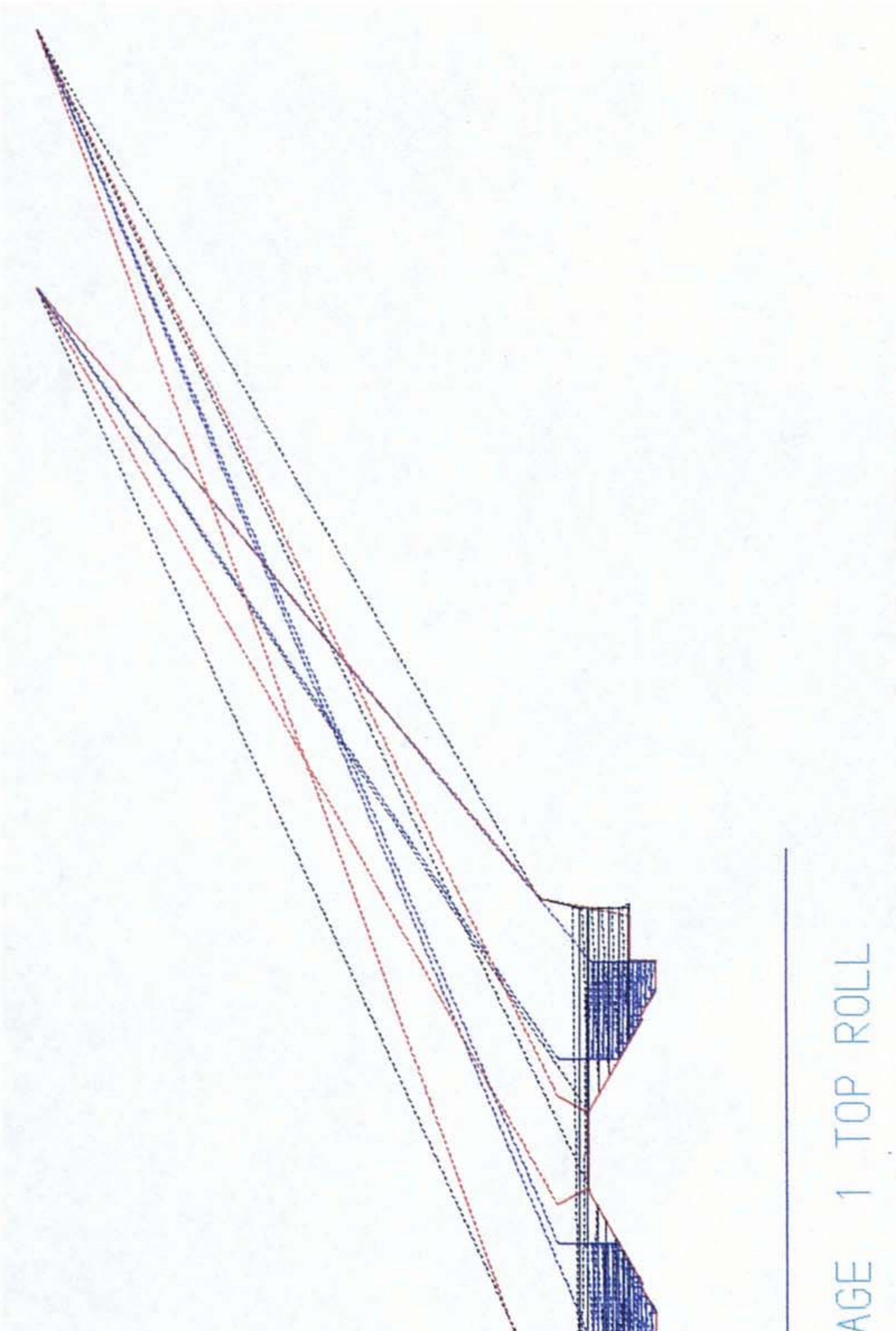
By using the roll editor program the designer can define the final roll profile, the output from the roll editor (the E-file) contains the digitised version of this profile and forms the input to the computer aided manufacture (CAM) software.

Figure 4.1 details the programs which collectively form the computer aided manufacture software, namely :-

(1) Roll machining software
(2) Post processor software
(3) N.C tape checking software

The N.C tape production software consists of two main sections. The roll machining software interprets the roll geometry and the machining data to produce the cutter location file. (The cutter location file being a file which defines the tool movements in a machine independent form). The second program, the post processor takes the cutter location file and processes this into the N.C tape file. Since, in general, different machine tool controllers require differing N.C files the post processor is dedicated to a specific machine tool.

Figure 5.1 Cutter Path Drawing



5.2 ROLL MACHINING SOFTWARE

Having completed the roll design it remains to produce the N.C tape in the most efficient manner. The purpose of the roll machining software is to produce the cutter location file by considering a combination of geometric and technological data. The geometric data is provided by the edited roll file. The following sections describe the technological data, namely, the machining commands and the tool library.

5.2.1 MACHINING COMMANDS

As with the whole CAD/CAM system, the philosophy in the machining software is to give the designer maximum flexibility whilst reducing the data input to a minimum. The input to the machining software comprises a series of numeric answers to an interactive dialogue. As this information is received the resulting cutter path is output to the terminal, thus the designer recieves a pictorial representation of metal removed and can easily visualise the remaining metal and decide how best to remove it. Figure 5.1 shows an example of a cutter path plot drawing.

Firstly, when deciding on the machining commands, the designer must divide the roll contour into 'machining areas', then he must decide the appropriate machining method and finally he must choose the appropriate cutting tool and cutting conditions (cutting speed and feed rate). Four machining methods are available with the roll machining software, namely : roughing, grooving, pocketing and finishing.

The blank diameter is calculated automatically within the machining software by calculating the maximum diameter of the roll and adding a clearance of 10mm. The blank size is then taken as the next largest blank size from the following list of standard diameters.

115, 130, 145, 160, 175, 190, 210mm

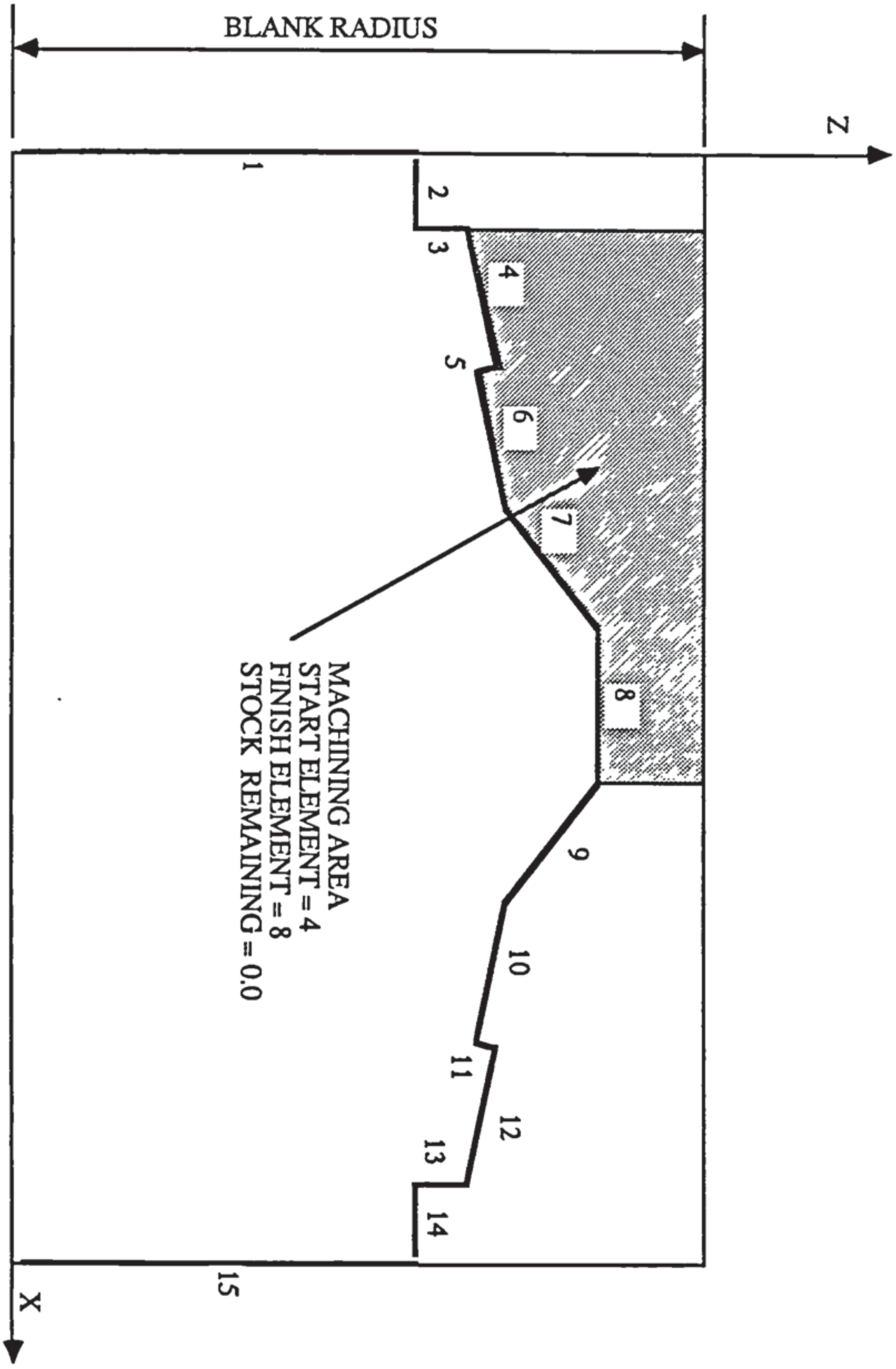
Where the calculated diameter is greater than 210mm, the designer must input the blank diameter.

The roll profile is a series of linear and circular contour elements each of which is assigned a number in the edited roll file, (where the element numbering is illustrated in Figure 5.2). The machining area is defined by inputting a start element number and a finish element number, vertical lines forming the two remaining boundaries . The direction of cut is determined by the relative values of the starting and finishing elements. If the starting element is less than the finishing element then cutting will be from left to right, if the starting element is less than the finishing element then cutting will proceed from right to left.

Clearly, with the exception of the finishing cut, there will always be a certain amount of stock left remaining, thus to fully define the machining area it is necessary to define the amount of stock which should remain after machining.

5.2.2 ROUGHING CYCLE

The roughing cycle is defined as follows, first the tool is positioned at the machine start point (at a distance 2mm from the machining area) at rapid traverse. Then the machining is performed as a series of three stroke cutting cycles, (see Figure 5.3A & B). The first stroke takes the tool from its previous position (N) to the cutting start point (P). The second stroke is the cutting stroke, parallel to the Z axis, from point (P) to point (Q), finally the tool returns at rapid traverse to point (R). The distance (T) is the finishing tolerance remaining. The depth of cut is defined by the dimension (D) and the point (R) is defined by the clearance value (C).



FIIGURE 5.2 ROLL MACHINING AREA

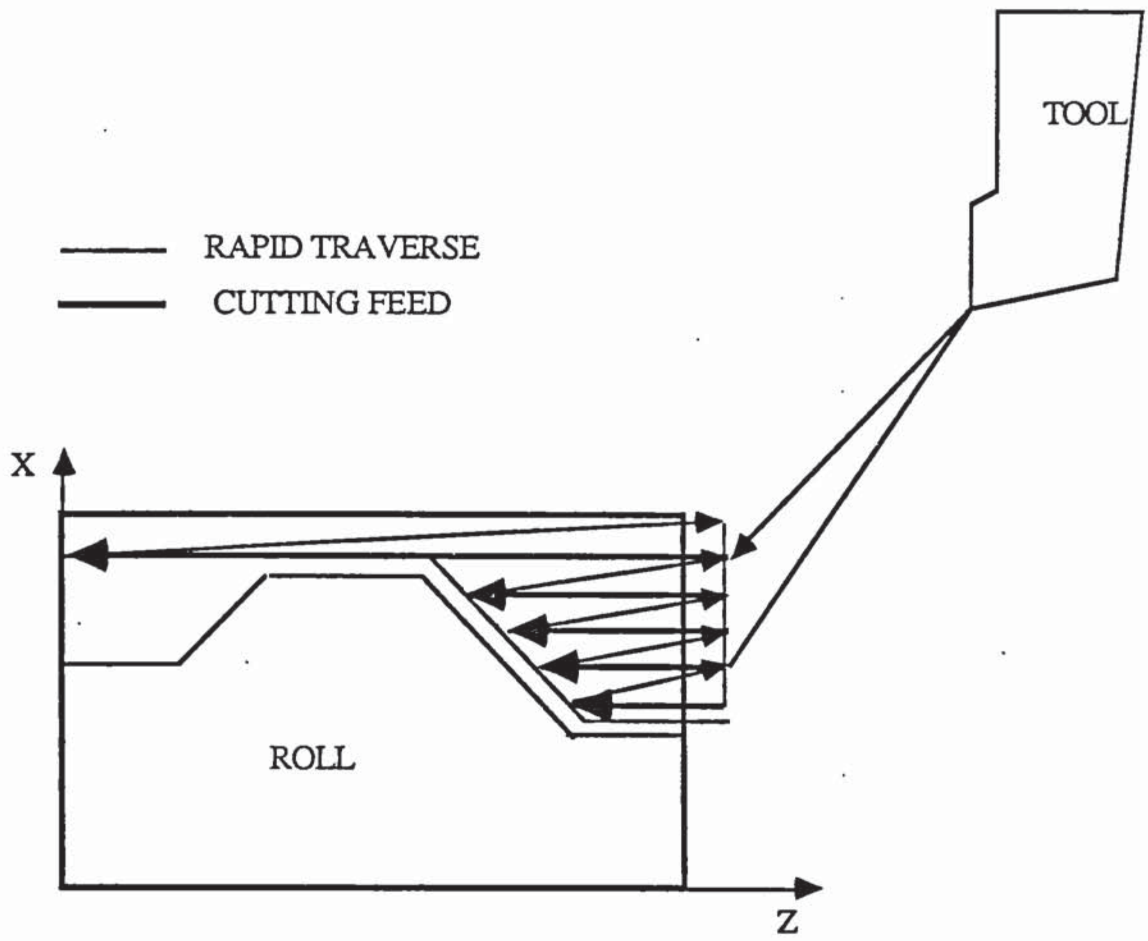


FIGURE 5.3A ROUGHING CYCLE

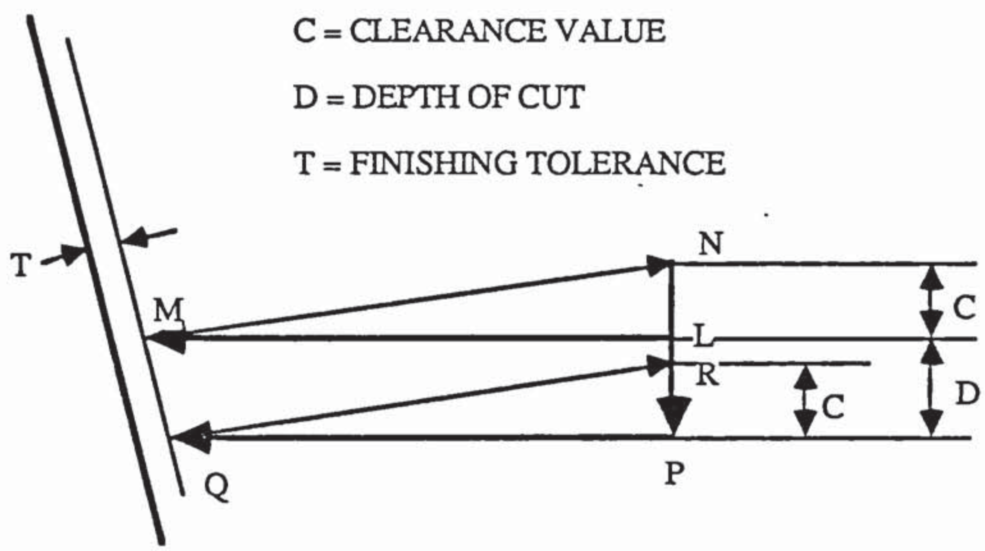


FIGURE 5.3B THREE STROKE MACHINING CYCLE

5.2.3 POCKETING CYCLE

The pocketing cycle is used to rough out concave roll profiles. For instance in Figure 5.4A the area ABCD would be left uncut by the roughing cycle. To rough this area a tool is used to "dig in" to the metal (where the clearance angle of the tool (CL) is greater than the cut in angle). When using the cycle, firstly the "cut in line" must be defined by nominating a point and the angle between the line and the axis.

The pocketing cycle is a four stroke cutting cycle, considering Figure 5.4B, the first stroke takes the tool along the cut-in lines (from (E) to (F)) to a depth of cut (D). The second stroke is the cutting stroke from (F) to (G) parallel to the X axis. The third stroke is to return the tool at rapid traverse to the point (H). Finally the tool will return to the point (F) and commence a further cycle.

5.2.4 GROOVING CYCLE

The grooving cycle is a further method of removing metal from concave areas by utilising a parting off tool to cut grooves parallel to the X axis. Considering Figure 5.5A, the grooving cycle is a three stroke cutting cycle, the first stroke is the cutting stroke parallel to the Z axis from the point (E) to the point (F), the second stroke is to return to point (E) at rapid traverse, the third stroke is to move parallel to the X axis a distance equal to half the distance of the cutter width.

5.2.5 FINISHING CYCLE

After having roughed, pocketed and grooved the machining area it remains to remove the finishing tolerance. This is performed by using the finishing cycle. The finishing cycle follows the roll contour from the starting element to the finishing element as shown in Figure 5.6.

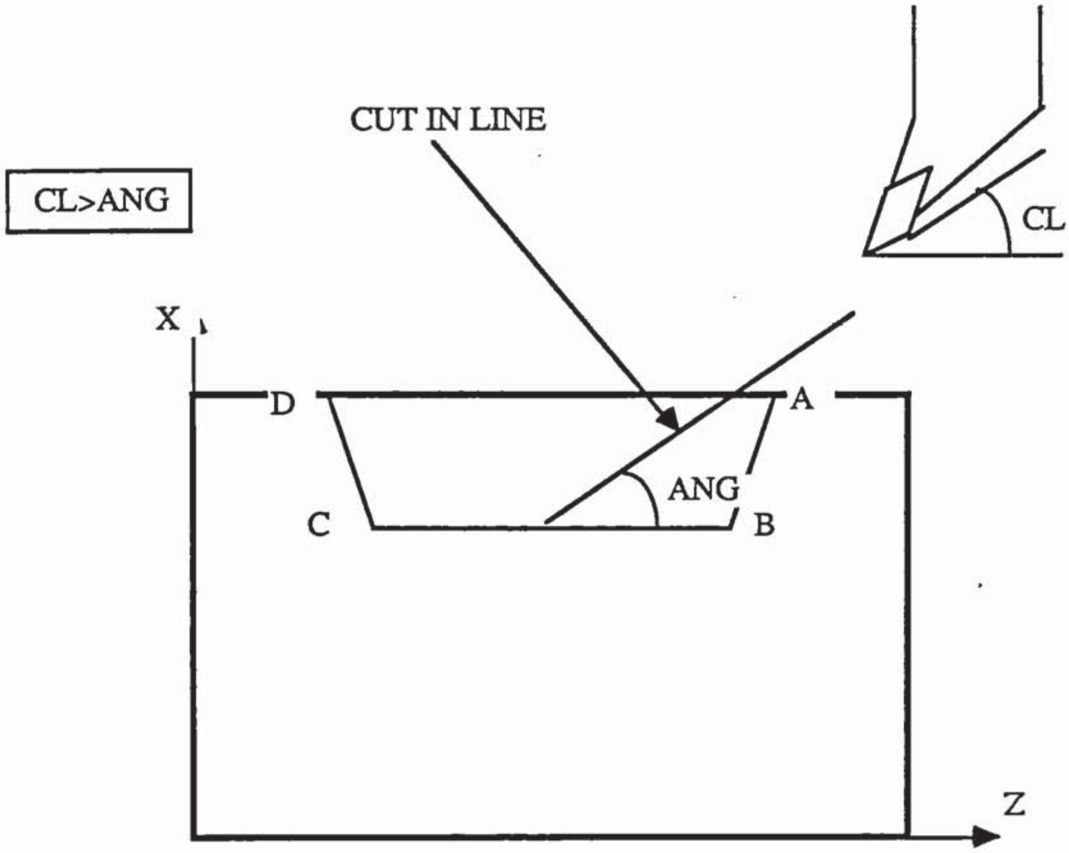


FIGURE 5.4A POCKETING CYCLE (ILLUSTRATING CUT-IN LINE)

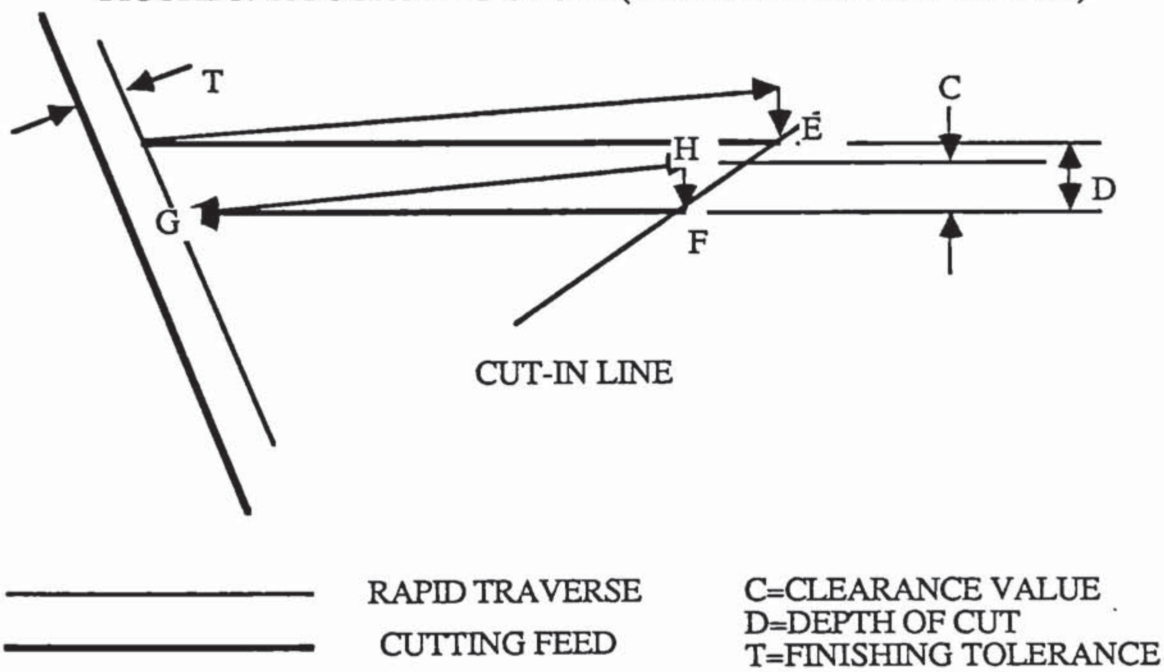


FIGURE 5.4B FOUR STROKE (POCKETING CYCLE)

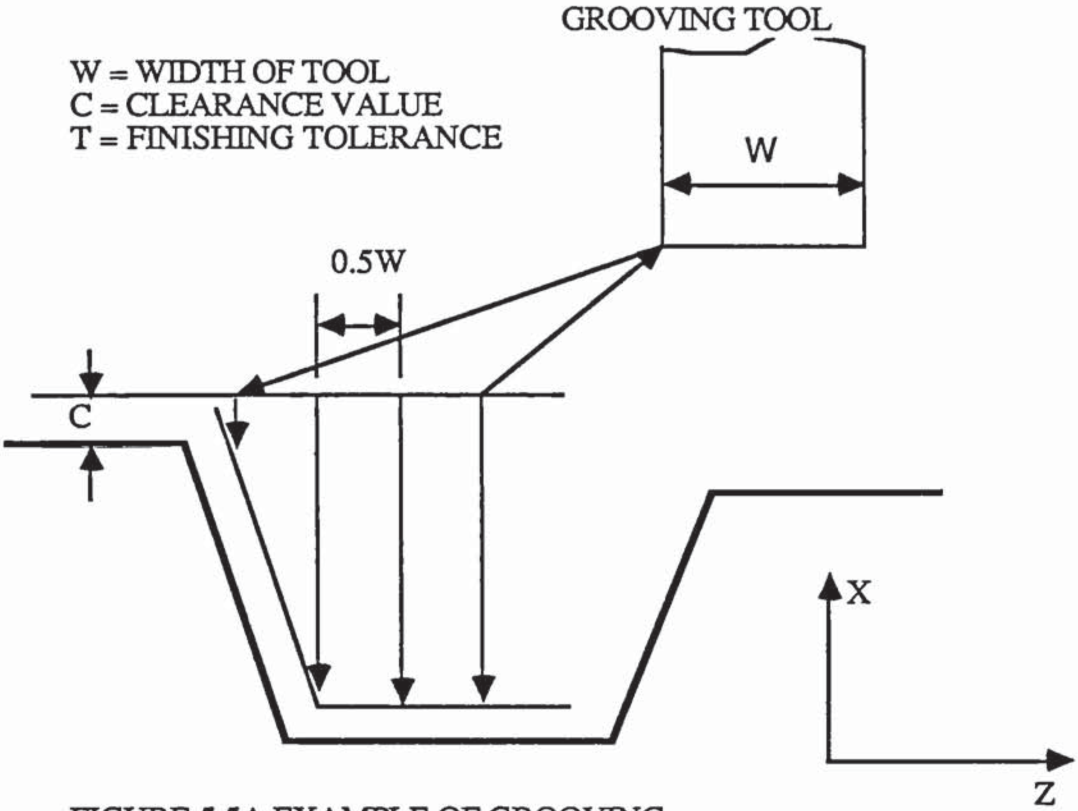


FIGURE 5.5A EXAMPLE OF GROOVING

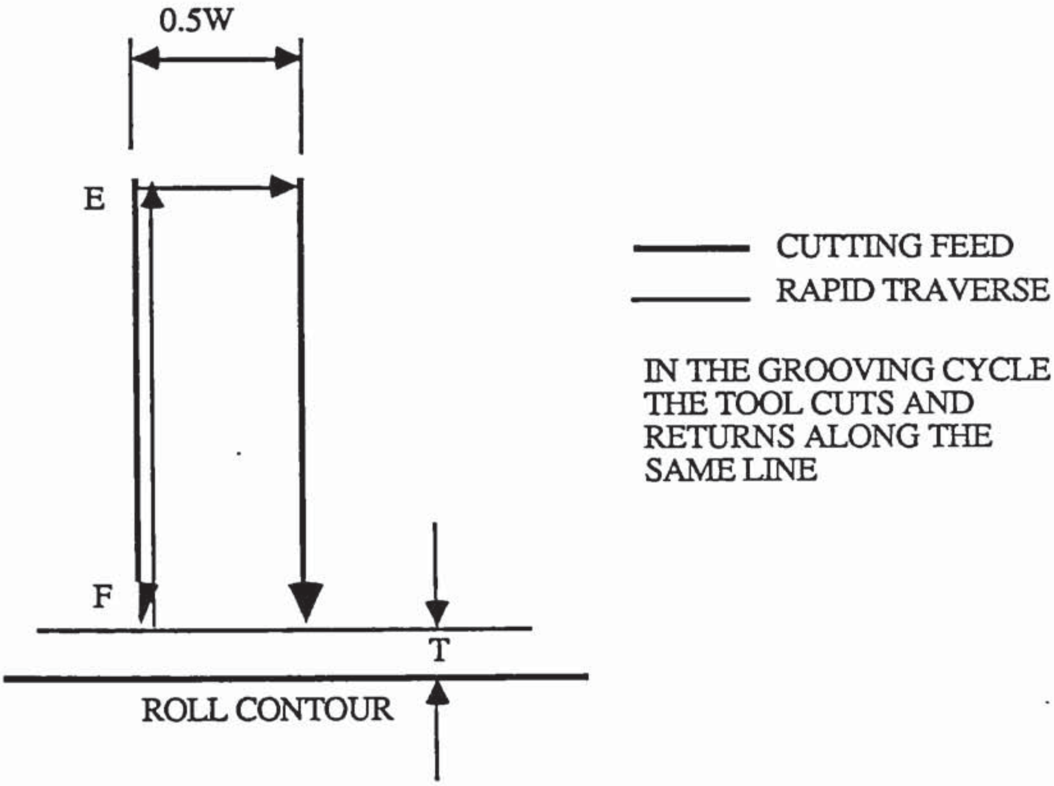
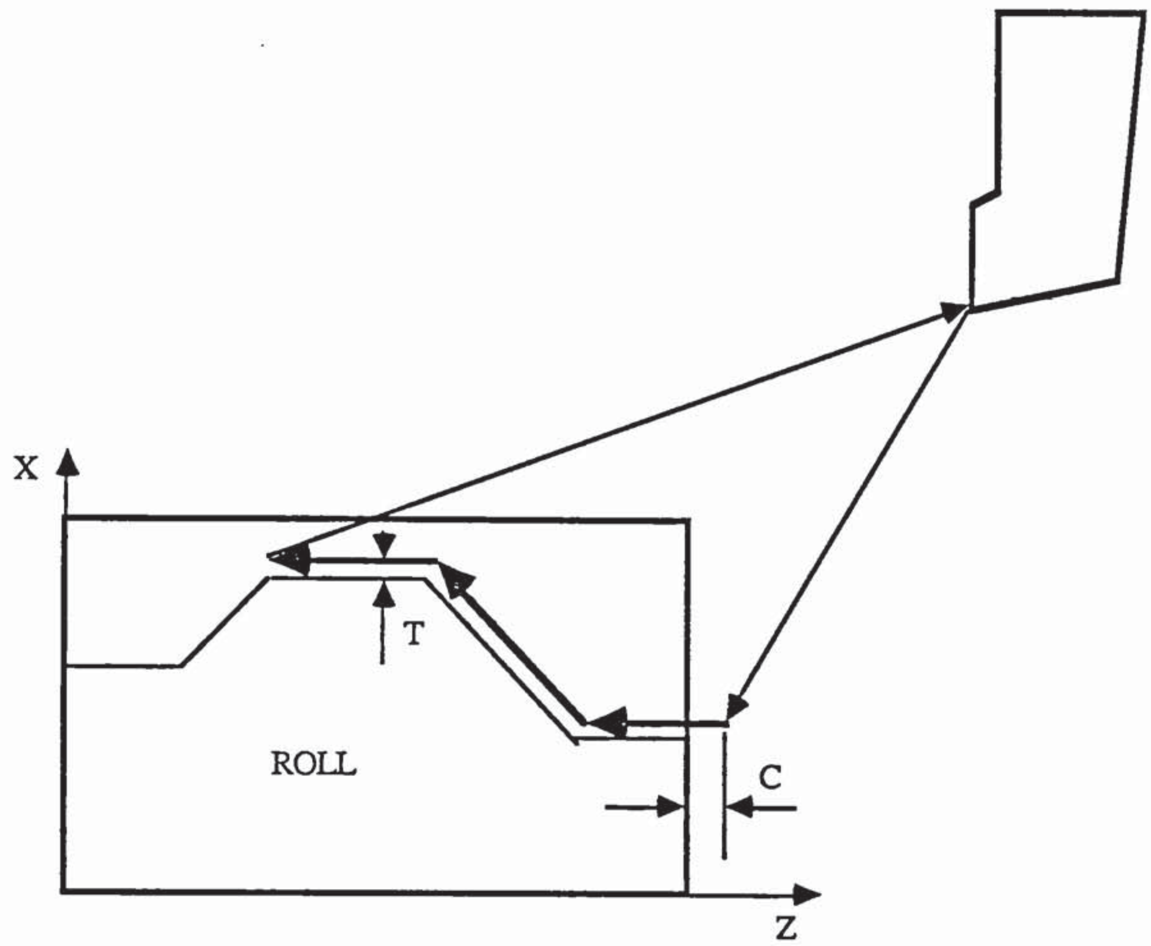


FIGURE 5.5B GROOVING CYCLE



RAPID TRAVERSE
CUTTING FEED

C = CLEARANCE VALUE

T = MATERIAL TOLERANCE (WHERE T = 0 FOR FINAL FINISHING)

FIGURE 5.6 FINISHING CYCLE

5.2.6 TOOL LIBRARY

As was mentioned previously, with each machining command it is necessary to define a tool by inputting a tool number. This number refers to the position of the tool in the turret of the lathe. Each lathe has a maximum number of tools which the turret can hold. On the Mori-Seki the maximum number of tools is twelve, where Table 5.1 details the standard selection of tools. The machining software has been designed to allow the use of five standard tool libraries, with the option, for the designer, of customising these libraries.

5.3 AUTOMATED ROLL MACHINING SOFTWARE

Chapter 3 described the conventional means of manufacture of form rolls and described some of the problems associated with the manufacture of form rolls. The previous section described how numerical control has been introduced and has alleviated many of the problems traditional to form roll manufacture. However, whilst the input to the machining software was simplified to as great an extent as possible, a study showed that a large part of the time spent in the rolform system (approximately 30%) was spent on the machining software. Additionally it was felt that, since the designer followed well defined procedures in most case, these cutting instructions could be generated automatically without detriment to the manufacturing process.

The procedures followed by the software in generating the cutting cycles, the cutting sequence, the appropriate cutting tool to remove the material, the cutting angle at which to enter the material, the optimum speed, the optimum feed and the optimum depth of cut are described in detail by Vasiliou[30].

TURRET POSITION	TOOL
1	5 mm BUTTON TOOL FINISHING
2	55 DEGREE RHOMBOID RH ROUGHING
3	35 DEGREE DIAMOND LH FINISHING
4	NOT IN USE
5	6mm RH PARTING TOOL
6	55 DEGREE ROMBOID LH ROUGHING
7	35 DEGREE DIAMOND RH ROUGHING
8	4.1 mm RH PARTING TOOL
9	NOT IN USE
10	35 DEGREE DIAMOND LH ROUGHING
11	35 DEGREE DIAMOND RH FINISHING
12	70 DEGREE COPYING TOOL

TABLE 5.1 TOOL LAYOUT

5.4 POST PROCESSSOR SOFTWARE

The output from the roll machining (or cutplot) software is the cutter location data (CLDATA) file. The purpose of the post processor is to convert the CLDATA file into a form legible to a particular numerical controller. It is unfortunate that, whilst, numerical control has become widely accepted, individual machine tools still require different programming codes and different tape formats, thus making post processing necessary. The post processor itself is a relatively simple program , for the most part it merely transposes information from one format into another. The system, presently, contains post processors for two machine tools although extra post processors can be written as required.

The information is read from the CL-FILE line by line and immediately translated into numerical coding. This information is written to both a file and the screen whilst the cutter path is also shown on the screen. An example of the N.C coding is shown in Appendix A. The N.C tape is obviously the binary representation of the alphanumeric coding in the tape file and is obtained by copying the N.C file to a paper tape punch.

5.5 N.C TAPE CHECKING SOFTWARE

The purpose of the N.C tape checking software is to allow the designer to obtain a graphical representation of the contents of an N.C tape file. This is useful if the designer, for whatever reason, manually edits an N.C file and then wishes to observe the cutter path of the edited N.C file. Occasionally when the designer is uncertain of the contents of a file he may wish to consider the tool path which results from that file. In a similar manner to the post processor the N.C file is read line by line and each line is interpreted graphically on the screen, thus, the tape checking program can provide an extremely useful facility for the designer.

5.6 SOFTWARE IMPLEMENTATION

The preceding sections have described the features and operation of the CAD/CAM software package. These programs are all written in the Fortran 77 programming language, this language was chosen because it is easily transportable whilst providing a wide range of numeric features. Compilers are available for Fortran on a wide range of computers whilst the language itself is standard requiring only minor alterations in transferral. Additionally, the GINO-F graphical package is used, this is a commonly available package which is largely device independent thus allowing a large range of output devices (terminals or graph plotters) to be connected.

Originally it was envisaged that the software would run on a single user workstation and accordingly an ICL PERQ was purchased. The PERQ combines a high resolution graphics screen with substantial processing capabilities, and whilst it proved ideal for running the software it was found to be over subscribed in practice. Thus, it was decided to move to a multi user system, with a central computer supporting a number of high resolution graphics terminals.

The development work at the university is carried out on a VAX 750 mini computer using Tektronix 4107 terminals. To run the system a micro VAX II was chosen, this shares the same operating system (VMS) as the VAX 750; therefore allowing relatively easy transferral of software. The micro VAX has 4MB of RAM and a fixed hard disk with 72 MB of file store, it has twin 7" floppy disk drives and a magnetic tape stream unit. Westward 2215's were chosen for the graphics terminals, these are monochrome units with a resolution of 1024 x 768 Pixels. To complete the system there is a Calcomp A0 Plotter, a paper tape punch and a printer, the system is described schematically in Figure 5.7.

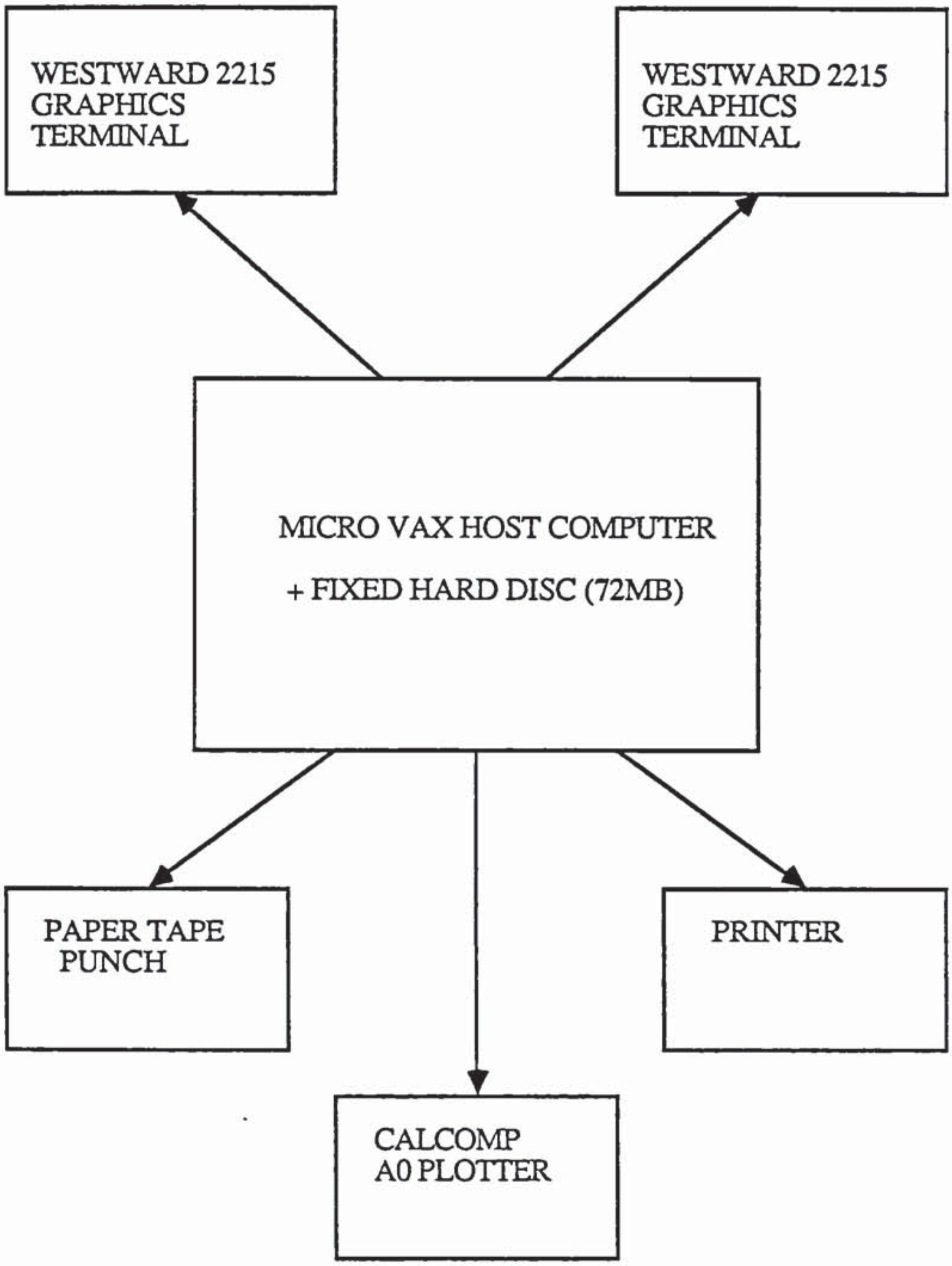


FIGURE 5.7 MULTI USER SYSTEM

The framework for running the CAD/CAM system in a multi-user environment is a series of VMS command language programs. In developing the multi user system considerable effort was invested into achieving two objectives. Firstly, that the system should be easily expandable, allowing additional users to be readily incorporated into the system. Secondly, that new users should become rapidly accustomed to the system. The individual programs in the system can all be accessed through a single command via a menu structure. (Where the CAD/CAM system menu is shown in Figure 5.8). Parallel to the CAD/CAM system is the help system which gives access to a series of help files which are intended to guide the designer around the CAD/CAM system (Figure 5.9).

In connecting the Westward terminals into the system the following practical observations were deemed worthy of note. Firstly, the Westward terminals, by default, generate alphanumeric characters in the graphics mode by hardware. This can cause an incremental error in the plotting of drawings on the screen when non standard sized characters are drawn. Secondly, whilst the Westward terminals have logically separate alphanumeric and graphical screens, having invoked the graphics mode succeeding text will be sent to the graphics screen. These two problems can be overcome, using Gino, by use of the Sofcha and Chamod routines.

5.7 MACHINING OF FORM ROLLS

The ultimate objective of the CAD/CAM system is, of course, to produce correctly profiled form rolls, using the media of N.C it is possible to efficiently and accurately achieve this. However the accuracy of N.C (or any) machining can easily be affected by careless tooling or workpiece setup. Thus the process of machining form rolls must also be carefully planned if the advantages of using CAD/CAM are not to be negated. In order that a complete roll profile may be machined on a single set up the roll is held on a purposely defined mandrel (described in Figure 5.10).

ROLFORM CAD/CAM SYSTEM
=====================

	PROGRAM	KEYWORD
(1)	INPUT SECTION DATA	SECTION
(2)	RERUN SECTION ON SCREEN	NSECTION
(3)	RERUN SECTION ON PLOTTER	MSECTION
(4)	INPUT FLOWER PATTERN DATA	FLOWER
(5)	RERUN FLOWER PATTERN ON SCREEN	NFLOWER
(6)	RERUN FLOWER PATTERN ON PLOTTER	MFLOWER
(7)	RUN TEMPLATE PROGRAM	TEMPLATE
(8)	RUN TEMPLATE ON PLOTTER	MTEMPLATE
(9)	INPUT ROLL DESIGN DATA	DESIGN
(9A)	INPUT ROLL D-DATA IN SINGLE STAGE	SDESIGN
(10)	RERUN ROLL DESIGN ON SCREEN	NDESIGN
(11)	RERUN ROLL DESIGN ON PLOTTER	MDESIGN
(12)	RUN WIRE FRAME ON SCREEN	WIRE
(13)	RUN WIRE FRAME ON PLOTTER	MWIRE
(14)	RUN PLAN/SIDE ON SCREEN	VIEW
(15)	RUN PLAN/SIDE ON PLOTTER	MVIEW
(16)	EDIT ROLL DESIGN	AEDITOR
(17)	INPUT CUTTING COMMANDS	CUTPLOT
(18)	RERUN CUTPLOT ON SCREEN	NCUTPLOT
(19)	RERUN CUTPLOT ON PLOTTER	MCUTPLOT
(20)	RUN POST PROCESSOR	MFPOST
(21)	CHECK NC TAPE ON SCREEN	CHK
(22)	CHECK NC TAPE ON PLOTTER	MCHK

PLEASE TYPE KEYWORD TO SELECT A PROGRAM

FIGURE 5.8 SYSTEM MENU

```
HELP FILE

HELP IS AVAILABLE ON THE FOLLOWING SUBJECTS

       SUBJECT                                          KEYWORD
       -------                                          -------
(0)    OVERVIEW (FOR THE FIRST TIME USER)               OVERVIEW
(1)    COMMANDS                                         COMMAND
(2)    INPUTTING A NEW SECTION FILE                     SECTION
(3)    INPUTTING A NEW FLOWER PATTERN                   FLOWER
(4)    INPUTTING A NEW ROLL FILE                        ROLL
(5)    EDITING A ROLL                                   EDIT
(6)    CREATING A CUTTER LOCATION FILE                  CUTPLOT
(7)    CREATING A N.C.FILE                              NCCREATE
(8)    CHECKING AN EXISTING N.C.FILE                    NCCHK
(9)    PUNCHING AN N.C.TAPE                             PUNTAP
(10)   ALTERING A TOOL LIBRARY                          TLIB
(11)   RUNNING.THE WIRE,PLAN,SIDE VIEWS                 WIRE
(12)   THE FILE NAMING SYSTEM                           FILE
(13)   COMPILING PROGRAMMES                             COMP
(14)   RUNNING FROM AN EXISTING DATA FILE               EXIST
(15)   DUTCHBEAD                                        DUTCH
(16)   SPRINGBACK                                       SPRING
(17)   UPDATING THE HELP SYSTEM                         UPDATE

PRESS  CONTROL/S TO STOP THE LISTING AND CONTROL/Q TO RESUME


PLEASE INPUT YOUR CHOICE OF KEYWORD
                            -------
INPUT 99 TO EXIT
```

FIGURE 5.9 HELP SYSTEM MENU

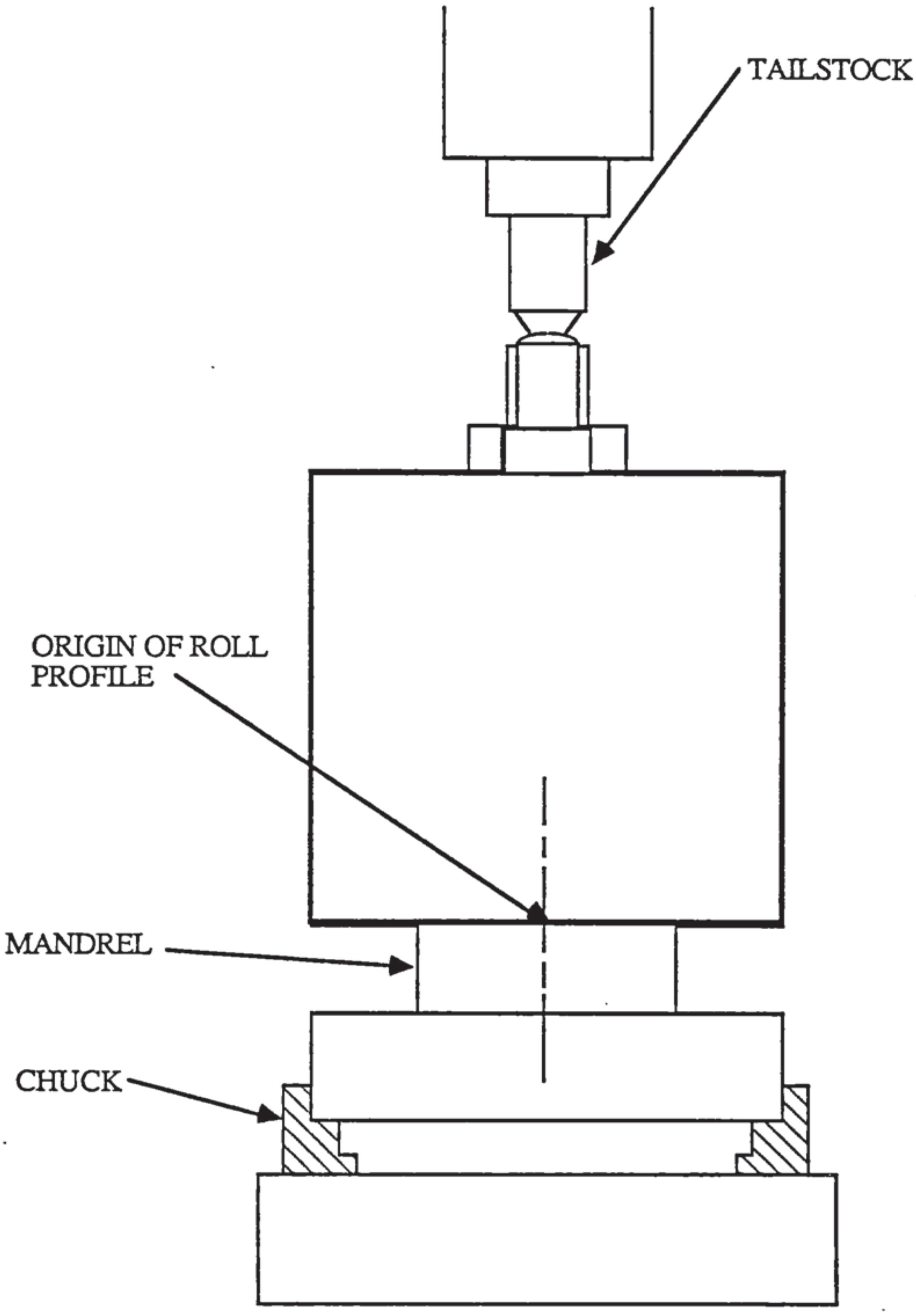


FIGURE 5.10 MACHINING SET UP

The mandrel also provides a datum from which to work from. A prerequisite of this method is that the roll blanks are prebored to the mandrel diameter and accurately turned to length, the roll blank must also be keywayed so as to fix the roll on the mandrel and the rolling mill spindle.

Machining of form rolls consists of two main stages, roughing and finishing, and a set of carbide turning tools have been supplied to perform these tasks. The tooling consists of left and right hand roughing tools, two parting off tools for roughing out concave areas (of 4.1mm and 6mm width), left hand and right hand finishing tools and a button tool. These tools are, of course, fully defined in the tool library.

5.8 THE BENEFITS OF CAD/CAM IN FORM ROLL PRODUCTION

There can be little doubt that the evolution of CAD/CAM techniques have revolutionised many aspects of industry with few large companies being unaffected by their emergence. The application of drafting packages, finite element packages and N.C tape preparation packages ,for example ,has become relatively common and the benefits of their application has been well documented. Similarly, in cold roll forming, several of the leading manufacturers have recognised the potential of CAD/CAM, and the application of CAD/CAM to form roll production has had significant and real benefits both economically and technologically. The benefits can be summarised into the following headings:

(I) Reduced lead times
(II) Fewer calculation errors
(III) Improved design
(IV) The development of a design data base
(V) More efficient manufacture

The lead times for producing form rolls have been substantially shortened when using the CAD/CAM system compared to when conventional methods were employed, this is largely because many relatively routine non design tasks which previously consumed much time have been automated. Since much cold roll forming is practiced in a "jobbing" environment, the ability to offer low lead times to ones customers is clearly a considerable asset, and thus this is one of the most important benefits.

One of the major reasons for the increasing application of computers is their ability to perform numeric calculations quickly and accurately. This is particularly relevant in form roll production, where there are large numbers of calculations and where errors can be extremely costly. Since, by the way the CAD/CAM system has been designed, all information is input only once, the potential for making errors is extremely limited. Additionally, the computers ability to handle large numbers of calculations has allowed a more sophisticated method to be used for estimating the strip length thus providing improved accuracy over conventional methods.

The CAD/CAM system has not only automated many of the relatively routine, non-design tasks, but it has also resulted in an improved design. Firstly, the removal of these peripheral tasks has allowed the designer to concentrate on pure design tasks thus improving design. Secondly, since the data input to the system has been reduced to a minimum and since the design is totally defined by numeric data files it is very simple to alter the design, thus it is possible to examine several designs and choose the most suitable. This would be difficult with conventional design techniques since changing the design will often result in a great deal of work. Finally, springback is traditionally a major problem in cold roll forming, particularly where the designer does not recognise that springback is likely to be a major problem , the computers ability to handle large numbers of calculations has allowed the percentage composite element lengths to be calculated automatically thus improving design by restricting springback to permissible levels.

Since the entire design and manufacture process can be defined by a small number of relatively short data files, it is possible to retain the entire design for any job on some suitable media (such as magnetic tape or floppy or hard disks). Thus it is possible to build a data base of past designs which can readily be recalled and examined. Since drawings can be automatically and quickly produced it is no longer strictly necessary to maintain large numbers of drawings of past designs (although it may be desirable for other reasons).

The benefits that have resulted from the new manufacturing methods are of two main types, those that are peculiar to form roll production and those that are commonly attributed to the introduction of numerical control in general (and thus have been well documented).

The principal limitation. of conventional manufacture of form rolls is the need to produce an intermediate template where high levels of skill are required to both produce and interpret this template. The CAD/CAM system eliminates the need for the template by transferring information by means of an N.C tape, this results in reduced lead times and more efficient and accurate manufacturing.

5.9 LIMITATIONS OF THE CAD/CAM SYSTEM

The CAD/CAM system developed at Aston University has, then, numerous significant benefits, the major examples of which are summarised in the previous section. The system has been implemented at the collaborative company and found to be successful in operation. However, whilst both the design and manufacture of form rolls can now be carried out far more efficiently than previously there is still one major limitation of the system which must be noted. This is, whilst form rolls can be produced quickly, accurately and economically using the system, the rolls themselves must be machined and set on the mill before the roll design can be stated satisfactory or unsatisfactory. Since, (as was noted in Chapter 3), there are little or no scientific principles to govern the design of form rolls then there can be no way of quantitatively assessing the design.

The complete system for finished section (as opposed to form roll) production can be described by Figure 5.11. It is quite possible then to require a complete redesign of the form rolls after testing them. When, one considers that a set of form rolls can cost up to £25,000, not withstanding the increase in lead time, this is clearly an undesirable situation, and so the systems principal limitation can be said to be the need to manufacture rolls and test them on the mill before the roll design can be stated as being satisfactory or unsatisfactory.

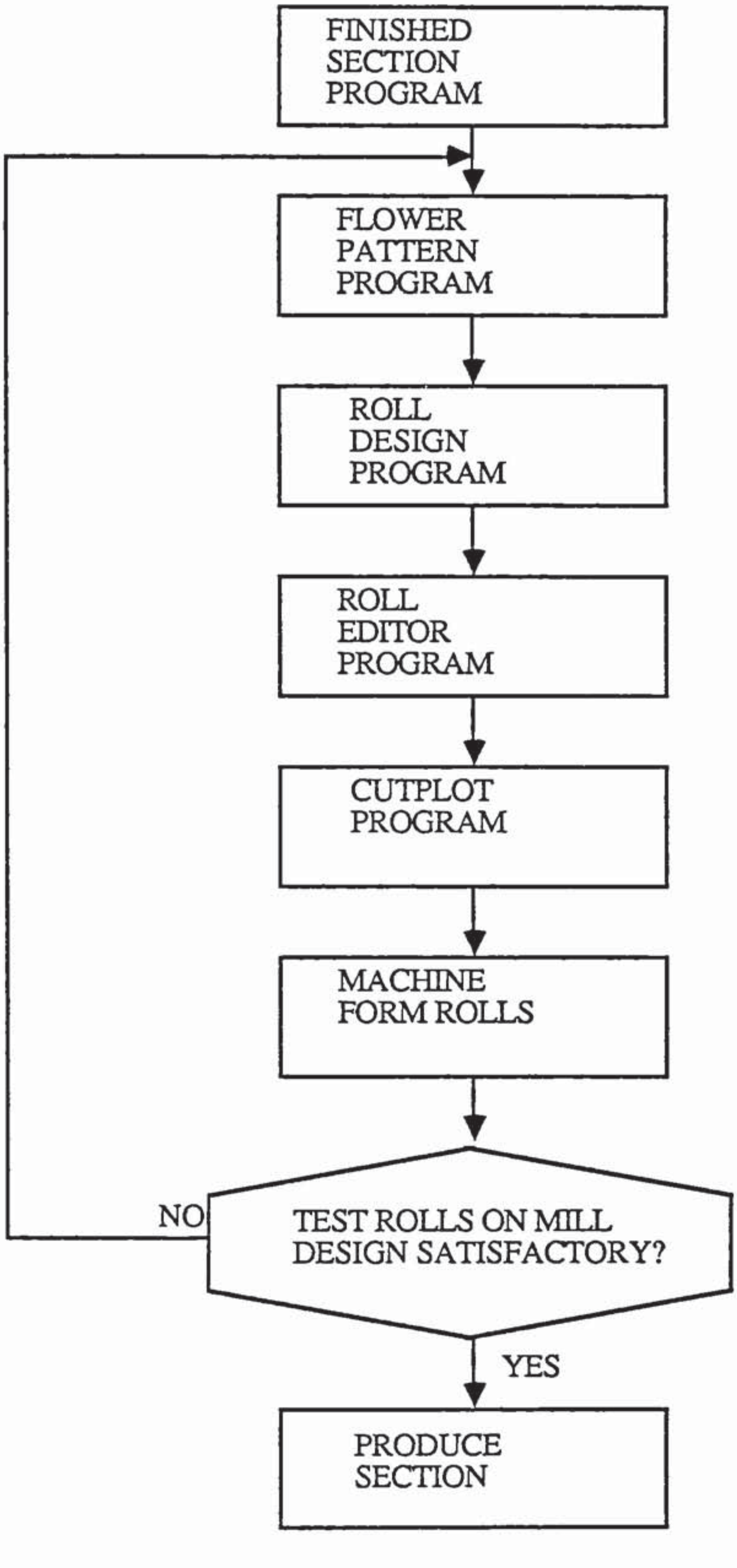


FIGURE 5.11 ROLL PRODUCTION SYSTEM OVERVIEW

CHAPTER 6

EXPERIMENTAL AND THEORETICAL ANALYSIS OF FORM ROLL DESIGN AND COLD ROLL FORMING DEFECTS

6.1 INTRODUCTION

The previous chapters have detailed the CAD/CAM system developed for the efficient design and manufacture of form rolls. The principal limitation of the system was noted to be the lack of scientific principles in flower pattern design and hence the need to manufacture rolls and test them on a rolling mill before a design can be stated to be satisfactory. From observation it will be noted that scientific principles, in general, are derived from two main sources, namely, theoretical analysis and experimental analysis. Thus, it will be enlightening to consider some of the research that has been performed into the experimental and theoretical analysis of form roll design.

For a metal forming process as economically important as cold roll forming it is, at first sight, surprising how little study has been directed, either experimental or theoretical, into the fundamentals of the cold roll forming process. However, on closer observation the reasons for this will become apparent and by studying these reasons the most suitable method of analysis will similarly become more apparent.

6.2 EXPERIMENTAL ANALYSIS OF FORM ROLL DESIGN

The experimental investigation of cold roll forming can be considered under three main sections.

(I) Fundamental studies of roll forming

(II) Investigations into "optimum" roll pass schedules

(III) Investigations into specific sectional problems, the occurance of these problems and the means of reducing these problems.

A fundamental study of roll forming refers to research which is not orientated to solving a particular problem, i.e. restricting the occurance of a particular defect or "optimising" the form roll design for a particular section, but is concerned with understanding the nature and interrelation of the parameters which define the cold roll forming process in general.

Figure 6.1, details those parameters which are known to define the cold roll forming process, obviously any study which attempted to look overall at all of these parameters would be immense. Thus, there have been very few studies which can be classified as fundamental and those that exist have been of a piecemeal nature when viewed within the context of Figure 6.1. Some of the more interesting fundamental studies are described below.

Masuda et al[31] investigated the cold roll forming of circular arcs with respect to the shape of metal between passes (which they concluded could be treated as a circular arc), the states of strain in the metal between passes and the power and torque required to form the arc. Additionally an expression was derived for the calculation of power for the rolling of circular arcs.

Sarantidis et al[32] were concerned with the cold roll forming of channel sections. In particular, the states of strain in the metal and the distribution of deformation between passes were investigated. As with all of these fundamental studies only a very simple section was considered. Jimma and Morimoto[33,34] also investigated the cold roll forming of channel sections , determining the strain fields by a method detailed in (33) and hence calculating the residual stresses and bending moments by a method detailed in (34) .Suprisingly a metal with a large tendency to springback, stainless steel, was chosen to

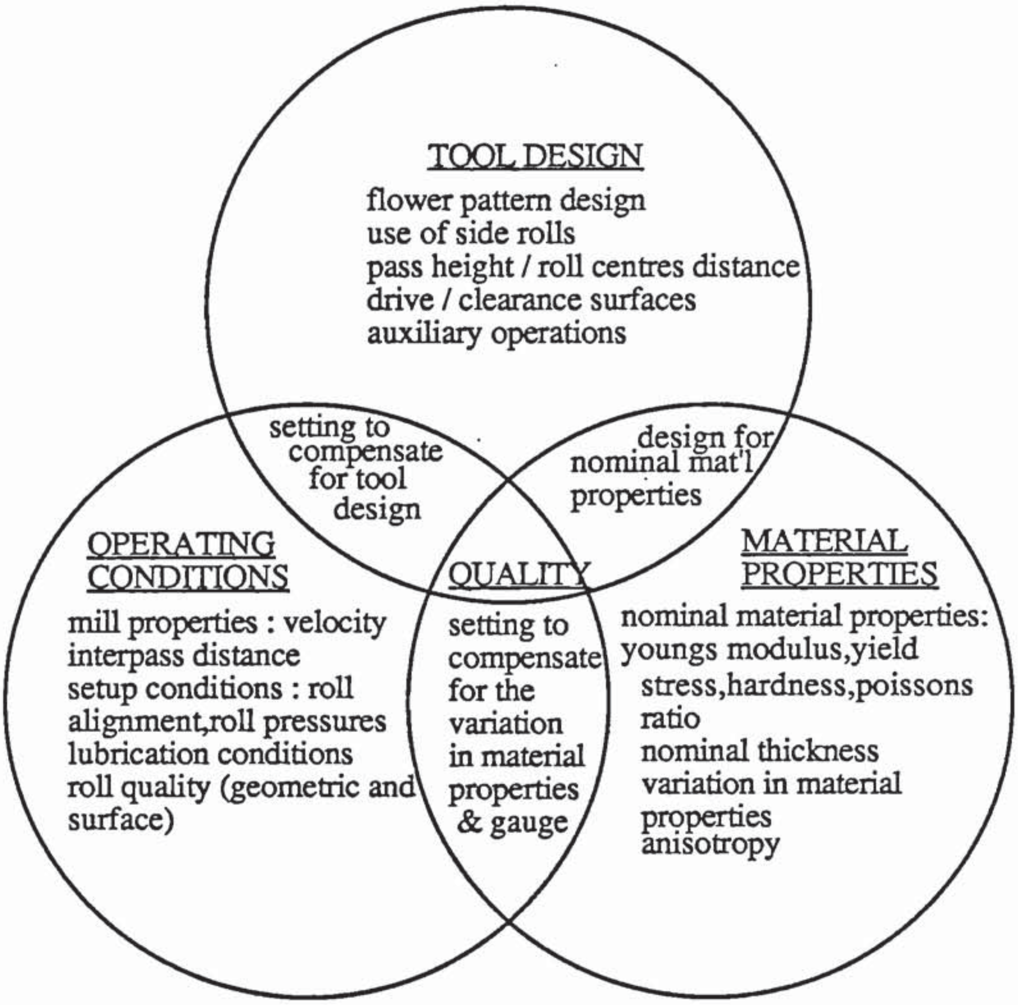


FIGURE 6.1 FACTORS DEFINING THE COLD ROLL FORMING PROCESS AND AFFECTING SECTION QUALITY

form the test material.

Investigations of roll pass schedules and "optimum" roll design can be considered studies of a fundamental nature where all of the parameters are fixed except those pertaining to the roll design. A major problem with optimising roll design is the difficulty in deciding on some statement of quality which can be optimised or at least satisfied by a particular roll design. Sectional quality is in practice a function of many interrelated parameters defining geometric accuracy and surface quality.

Thus, experimental attempts to obtain "optimum" roll design, in practice achieve adequate roll design. For instance Jimma and Ona[35] attempted to find the "optimum" roll pass schedules for the production of two channel section in three different materials. Forty two combinations of rolls were tested from the seven pairs of rolls with angles 15^{o}, 30^{o}, 45^{o}, 60^{o}, 75^{o}, 85^{o} and 90^{o}.

From these 42 combinations those combinations which prevented surface damage and edge wave were noted as adequate, the roll gaps which minimised the longitudinal curvature were sought and it was noted that a straight product can be roll formed without adjusting the roll gap if proper roll pass schedules are chosen.

The conculusions, then, were that for a particular mill, for two particular channel sections in three particular materials certain combinations of rolls were found to be adequate whilst others were found to be inadequate. Whenever any of the parameters listed in Figure 6.1 are altered the conclusions become inapplicable.

Thus, whilst Jimma and Ona took a ,perhaps necessarily, rather unimaginative approach, it can be seen that any attempt to derive a specific optimum flower pattern design experimentally will be labourious whilst any attempt to derive optimum flower patterns for the general section will be a study of immense proportions.

There appears to have been more work performed under the third grouping than the other two, that is work which has been directed towards solving a problem with a specific section, which is in production or is in the process of going into production. This would appear to reflect, both, the pragmatic nature of cold roll formers and, as has been noted previously, the inherent difficulties in the fundamental study of cold roll forming.

There are many examples of this type of research which have been documented and almost certainly many more examples which have gone undocumented. Some of the more interesting examples are listed below, Trishevskii et al[36] investigated the production of trapezoidal "corrugated" sections and in particular the problem of longitudinal camber and cross camber. This, they found to be due to the different levels of straining in the bends of the upper and lower ridges of the section. They knew that the straining could be controlled by varying the radius of curvature of the bend and hence by experimentation found radii of curvature for the upper and lower ridges which equalised the longitudinal straining and hence restricted the occurance of cross and longitudinal camber in that specific section using that specific design of form roll.

Similarly, Hira et al[37], investigated the cold roll forming of a type of wide panel (actually a siding board) and in particular the section defect known as "web-buckling" or "pocket wave" or "oil canning" and determined a ratio of web to thickness above which this is likely to take place. They then proceeded to consider the effects that material properties had on web buckling and hence were able to recommend suitable steels for the manufacture of the section.

Suzuki et al[38] investigated the cold roll forming of a wide profile with trapezoidal grooves and in particular the effect of various parameters on the occurance of such defects as pocket wave, corner buckling and crack propogation. Interestingly, they also noted the problem of stating overall section quality (and hence observing the effect that varying process parameters has on section quality).

Perhaps the foremost researchers in this area are Jimma and his co-workers, particularly Ona, who have carried out a campaign of research of this type. Some of the more interesting examples are listed below. A common problem in cold roll forming is end flare , hence they investigated the distortion near the cut-off edge for channel, top hat and C channel sections and thus developed formulae for suitable overbend angles[39]. Also[40] they investigated methods of eliminating defects which are common in the forming of assymetric channels such as twisting and curving. In reference (41) an investigation is made into the occurance and avoidance of edge buckling, corner buckling and cracking in the forming of wide panels. The conclusion was reached that edge buckling does not occur where the ratio of flange to thickness is less than 40. Similarly[42], they investigated the means of controlling "waviness" in trapezoidal sections by both redesign of section and by redesign of tooling.

A study which can be considered as partly fundamental and partly problem orientated has been made by Bhattacharyya[43] , who investigated the longitudinal straining in the rolling of a channel section and the roll designs which obtain a straight product using the minimum number of passes.

To a certain extent work which falls into category (3) is carried out by all roll formers, in that, often roll designs are modified and rolls remachined in order to reduce the occurance of specific defects. However, in most cases, such testing is carried out too unscientifically to justify the use of the word experimental.

To return, then, to the original problem of the need to manufacture rolls and test them on the mill before the design can be stated satisfactory or unsatisfactory. Considering the three types of research isolated earlier. Namely:

(i) Fundamental studies of roll forming

(ii) Investigations into "optimum" roll pass schedules.

(iii) Investigations into specific sectional problems, the occurance of these problems and the means of reducing these problems.

From considering Figure 6.1 and reviewing the fundamental studies that have been performed, it is obvious that fundamental research is an extremely laborious and time consuming process. Whilst, such studies provide extremely valuable information they are unlikely to directly provide guiding scientific principles for form roll design in the near future.

Attempting to develop "optimum" flower patterns experimentally incurs three major difficulties. Firstly, there is no single parameter or combination of parameters which quantifys the quality of cold rolled sections . Therefore whilst it is possible to state when a roll design produces an adequate finished section it is difficult to state when a design is optimal. Secondly, there are so many variables available to the designer that such studies are inevitably very time consuming. Finally in order to achieve the ultimate aim of producing consistently effective roll design there is the additional problem of interpolating from roll designs which are known to be effective to roll designs for some other section.

The third type of research yields valuable general information on types of section defect, but is mostly concerned with testing and designing rolls to produce a specific section adequately. Since the aim is to minimise this work as much as possible then the value of this approach is limited.

6.3 THEORETICAL ANALYSIS OF FORM ROLL DESIGN

When reference is made to the theoretical analysis of form roll design this is, of course, referring to the theoretical analysis of the effects of form roll design on the deformation of the sheet metal resulting from the passage through the form rolls.

Cold roll forming is a particularly complex metal deformation process to analyse for several reasons. Firstly, nothing is known of the shape of the metal in the regions between successive stages in the cold roll forming process. Also, the geometry of the deformed sheet metal is a highly complex three dimensional shape. Thus, in general, there has been little effort applied to theoretically analysing the deformation in cold roll forming.

A cursory examination of some of the common methods of metal forming analysis and their scope of application to cold roll forming will emphasis the reasons for this. The equilibrium method consists essentially of isolating a representative volume element in the body of the material and in observing the behaviour of this element as it passes through the working zone of the process. The method then examines the behaviour of the element by considering the equilibrium of the forces acting at any instant. The behaviour of the element is taken as representative of the behaviour of the whole body. However, given the complex three dimensional geometry of the deformed metal shape in cold roll forming it is difficult to envisage how a representative element may be isolated. Visioplasticity[44] is a method of analysis in which detailed stress and strain rate fields are derived from experimental observation of the velocity field in the deforming body. However, since the aim is to attempt to analyse the process in order to assess form roll design without the need to manufacture form rolls visioplasticity cannot be considered a suitable method of analysis in this case.

The finite element method[45] is now firmly established as a powerful general technique for the numerical solution of engineering problems. An advantage of the finite element method is that there are many commercially available finite element packages. Such a package was considered for modelling the cold roll forming process, however it was decided not to use such a package for the following reasons. Firstly, transportability, the model is intended to form part of a form roll CAD/CAM package and specifically to augment the roll form package described in the previous chapter. Clearly, using a finite element package severely compromises the transportability of the CAD/CAM package.Secondly, cold roll forming analysis requires the consideration of elastic and plastic deformation. Only the more sophisticated finite element packages can deal with non-linearity, and generally, only in a limited manner. Finally it is difficult to formulate a finite element analysis of the cold roll forming process without making assumptions that dramatically alter the nature of the process being considered. For instance, the strip between passes is not static but is, of course, in a dynamic state, where the state of stress in an element is dependent on the strain history of elements upstream from it, using the available finite element packages the condition is going to occur where an element upstream has plastically yielded and yet the element itself is being treated elastically.

A further method of metal forming analysis is limit analysis. Limit analysis will give, if fully used, two values for the power requirement, the lower bound and the upper bound. The lower bound, enforces the equilibrium equations and gives a power value which underestimates the load. The upper bound, relaxes the equilibrium equations but enforces the volume constancy and compatability equations and gives a realistic overestimate of power.

The upper bound technique, essentially, comprises of assuming a velocity distribution within the material, calculating the power required to overcome the resistance to deformation and the power to compensate for the frictional effects. The velocity field that minimises the computed power is taken as the actual one. This is called the principle of minimum energy or least resistance[46].

The most comprehensive theoretical study of cold roll forming would appear to be that carried out by Kiuchi et al[47] for the forming of tubes. Kiuchi, realised that the first step in modelling the roll forming process was in predicting the shape of metal between successive stages in the roll forming process. The work will be described more fully later but essentially it assumes that the shape of metal between successive stages of the roll forming process which minimises the power of deformation in the strip gives stress and strain fields which are good approximations of the actual stress and strain fields. This is obviously a statement of the minimum energy principle.

A further, less complex, analysis of the shape of metal in the cold roll forming of channels was made, again using a minimum energy approach, by Bhattacharyya[48]. Again this work will be detailed in a later section.

In his analysis, Kiuchi did not include a power term due to friction . It should be remembered that his aim was to model the shape of metal between successive passes of the roll forming process, and it is difficult to envisage how a power term for friction, which is dependent on the shape of metal between passes, can be derived. Thus it both seems reasonable , and also necessary, to assume that the power due to friction is not dependent on the shape of metal between passes. The following section will examine more closely the model suggested by Kiuchi and the results obtained.

6.4 PREVIOUS WORK OF KIUCHI

As was mentioned previously, a major analysis of cold roll forming has been performed by Kiuchi and his collaborators. The scope of the model was effectively limited, by the nature of the function defining shape, to simpler sections, primarily tubes (although channel sections and top hat sections have also been analysed). Kiuchi developed what he called a shape factor which geometrically described the shape of the metal strip between passes, and which is defined below (where the co-ordinate system is detailed in Figure 6.2).

$$S(x)=\sin[(\pi/2)(x/L)^n] \quad (1)$$

$$X = X(x,y)$$

$$Y = Y_1(y)+[Y_2(y)-Y_1(y)]S(x) \quad (2)$$

$$Z = Z_1(y)+[Z_2(y)-Z_1(y)]S(x)$$

Where Y_1, Z_1 are the Y and Z coordinates of the i th roll projected on the cross section which is perpendicular to the X axis at $X=X_1$.

And, Y_2, Z_2 are the Y and Z coordinates of the (i+1) th roll projected on the cross section which is perpendicular to the X axis at $X=X_2$

The strain field is calculated from this shape by making the additional assumption that the front and rear cross sectional profiles of the deformed sheet strip are always included in planes which are perpendicular to the X-axis and can move along the X-axis. Knowing the strain field, the stress field can be calculated by the application of a yield criteria and the constitutive equations developed by Yamada[49]. The variable N in equation (1) is then altered until the power of deformation is minimised, hence the shape and strain fields closest to the actual are achieved.

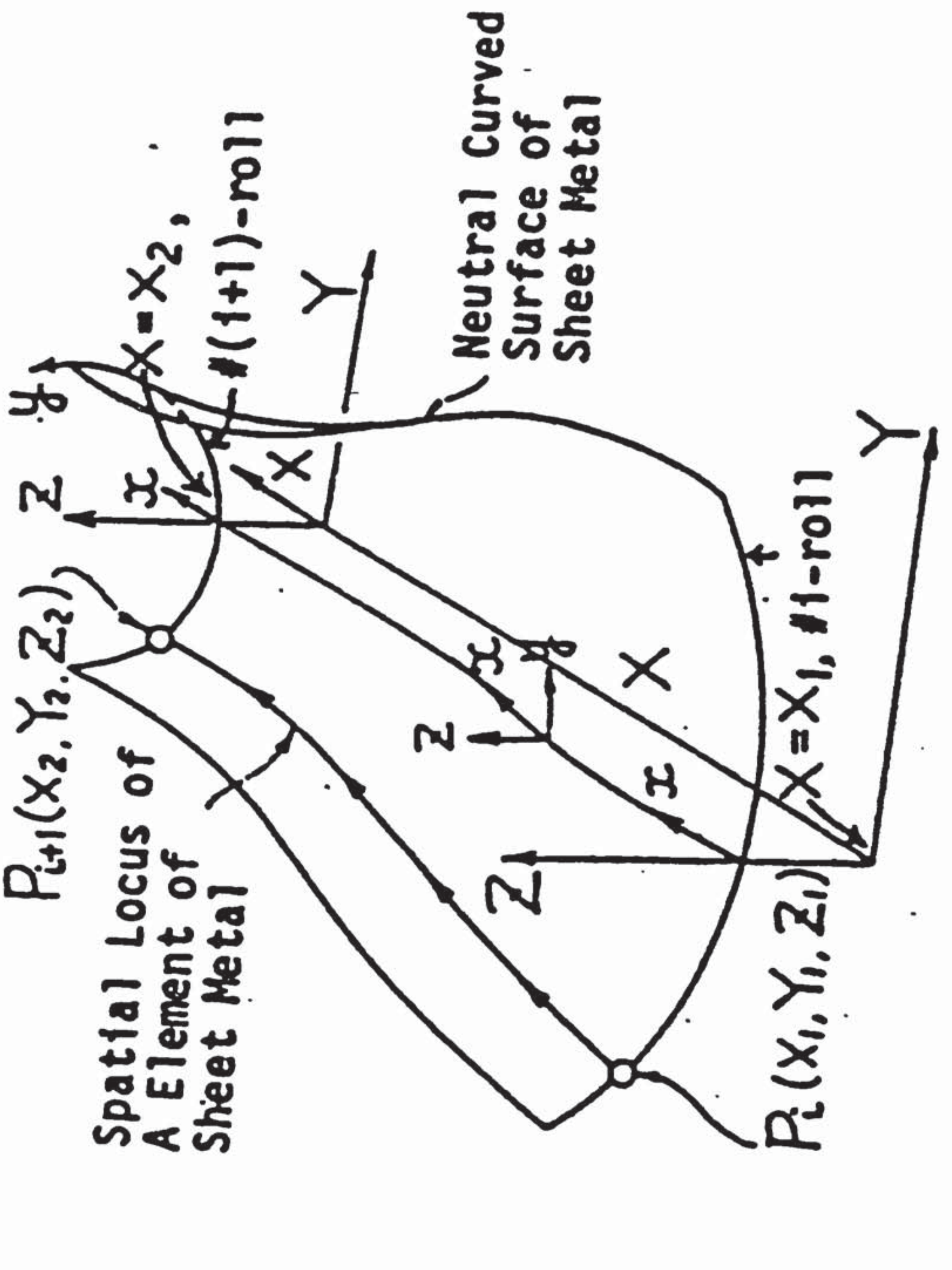


FIGURE 6.2 MODELLING OF TUBE ROLLING (AFTER KIUCHI)

Kiuchi then went on to develop 'optimum' flower patterns for tubes (using the results of the simulation) by either equalising the edge strain or the power at each pass. Interestingly, Kiuchi's simulation obtained the relationship that the power in forming a tube ($\dot{W}$) was related to the thickness (t) by the relationship.

$$\dot{W} \propto t^{2.18} \qquad (3)$$

Which is very close to the expression obtained by Hill[27] for the work done (W) in bending

$$W \propto t^{2} \qquad (4)$$

Equation (3) of course, includes the power due to stretching as well as the power due to bending.

Kiuchi's work can be said to be important because it is ,to date ,probably the most comprehensive attempt to model the cold roll forming process. However, whilst the results confirm the promise of this approach it was felt that the following criticisms could be made.

Firstly, the range of potential geometries of metal shape, defined by equation (1) ,was not supported by experimental data. If the model is to be as realistic, as possible, the variational defining the shape of metal between passes should reflect experimentally determined shapes.

Kiuchi's model is used primarily for the analysis of tube rolling, whereas, for the purpose of this project a more general model was considered necessary. For the general case a single variable defining the shape (as in equation (1)) becomes unrealistic. Clearly, as the number of active bends at each stage increases the complexity of defining shape increases and the number of variables must increase.

Additional parameters which influence the shape of metal between passes are not included in the model. In particular, the roll vertical centre to centre distance and the pass height (which together dictate the roll diameters) have a considerable effect on the deformation . This means ,in practice,that the model only considers the roll profile at the centre line and dismisses the effect of the roll shape away from this plane.

Finally, it was felt that a major weakness was the lack of experimental validation of the theoretical structure of the model by correlation of simulated and actual values.

6.5 PREVIOUS WORK OF BHATTACHARYYA et al

Whereas Kiuchi was mainly concerned with the forming of tubes, Bhattacharyya has concentrated on the forming of channel sections. Both experimental and theoretical research has been performed. The experimental work[43] concerned the measurement of longitudinal strain in the rolling of channel sections and the influence of the strain histories on the product straightness.

The theoretical work[48] is concerned with predicting the shape of metal between passes in the cold roll forming of channels, interestingly again a minimum energy approach has been adopted. It is assumed that no forming will take place in the pass until a certain point is reached,the distance from the downstream pass over which the forming takes place Bhattacharyya termed the 'deformation length'. Figure 6.3 details what is meant by deformation length .

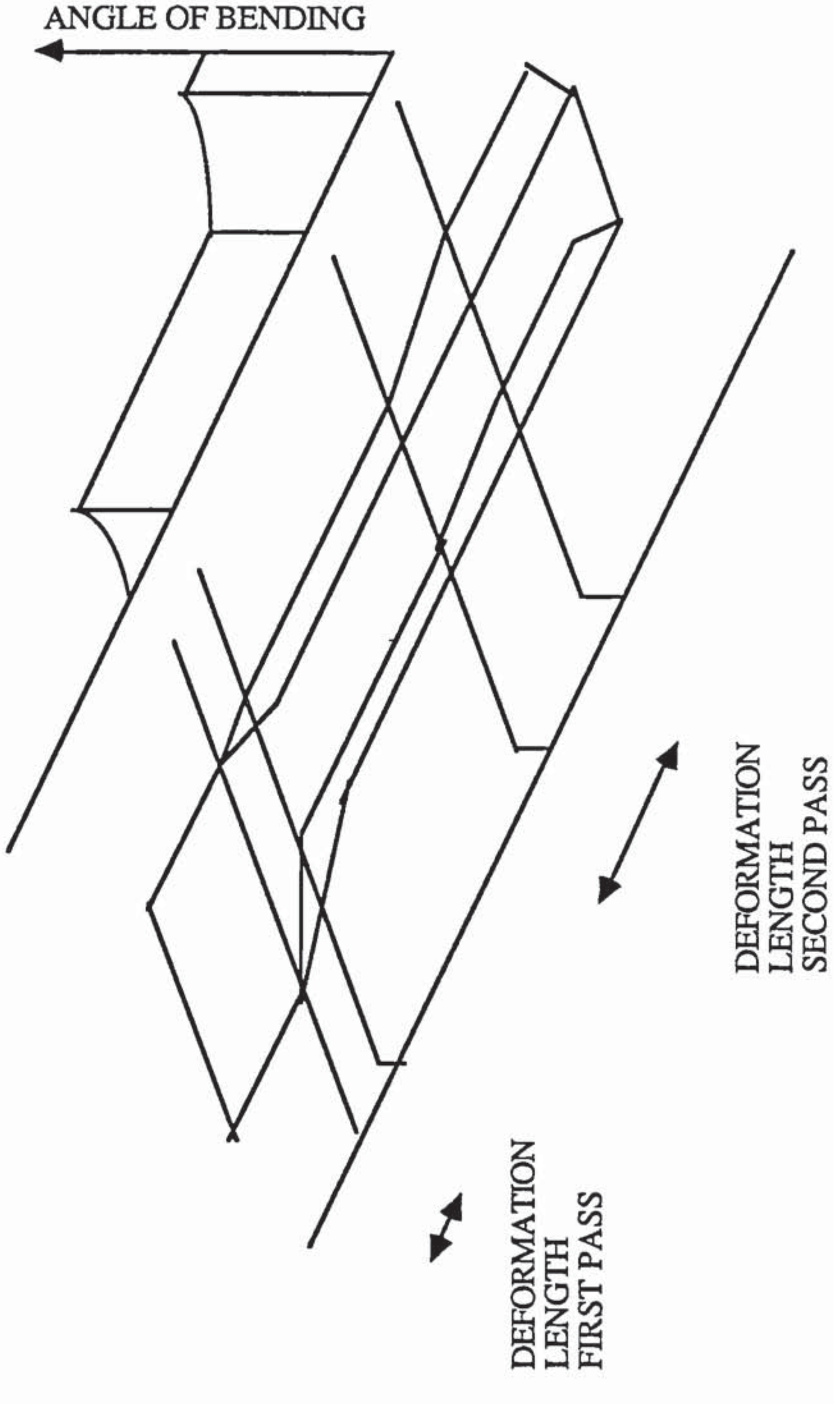


FIGURE 6.3 EXAMPLES OF DEFORMATION LENGTH

The assumptions that, (1) the material can be treated as rigid -perfectly plastic, (2) bending takes place only along the fold line ,(3) the leg adopts the shape which minimises the plastic work, are made. Expressions are derived for the work due to bending and due to stretching and hence for the total work. An expression is then obtained for the distribution of bending, which minimises the total work and by substituting the boundary values into this the following expression can be obtained for the deformation length.

$$L=a\sqrt{[(8a\theta)/(3t)]} \qquad (5)$$

where a is the leg length

t is the thickness

θ is the increment of angle

L is the deformation length

Experimental results are supplied and appear to correlate well with equation (5), the expression would seem to be both simple to use and accurate, thus it is surprising that it is not better known. The close similarity between theoretical and experimental results would seem to confirm the promise of the minimum energy approach.

6.6 EXPERIMENTAL AND THEORETICAL ANALYSIS OF SPRINGBACK

One aspect of metal forming, which has received considerable research both theoretical and experimental, which is of relevance to cold roll forming, is springback. Where springback is the name given to the tendency of sheet metal to return to its original shape.

As such, springback is a common problem encountoured in many sheet metal forming processes (including cold roll forming). Thus, whilst little research into springback has been primarily cold roll forming orientated there has been general research which is applicable to the cold roll forming process.

Gardiners equation[50] is the classic method of springback analysis, it provides an easily applicable method of estimating springback and as such seems to be commonly applied. Gardiners equation is derived in Appendix B and stated below :

$$R/r = 1-3[(RY)/(ET)]+4[(RY)/(ET)]^3 \qquad (6)$$

where

R=Radius before springback

r=Radius after springback

E=Young's modulus

T=Thickness

Y=Yield stress

and,

$$AR = A'r \qquad (7)$$

where A=Angle before springback

A'=Angle after springback

The limitation on the accuracy of equation (6) is imposed by the validity of the simplifying assumptions detailed in Appendix B. Nevertheless, since Gardiners equation provides an explicit statement of springback (for the general case), it provides a very useful approximation.

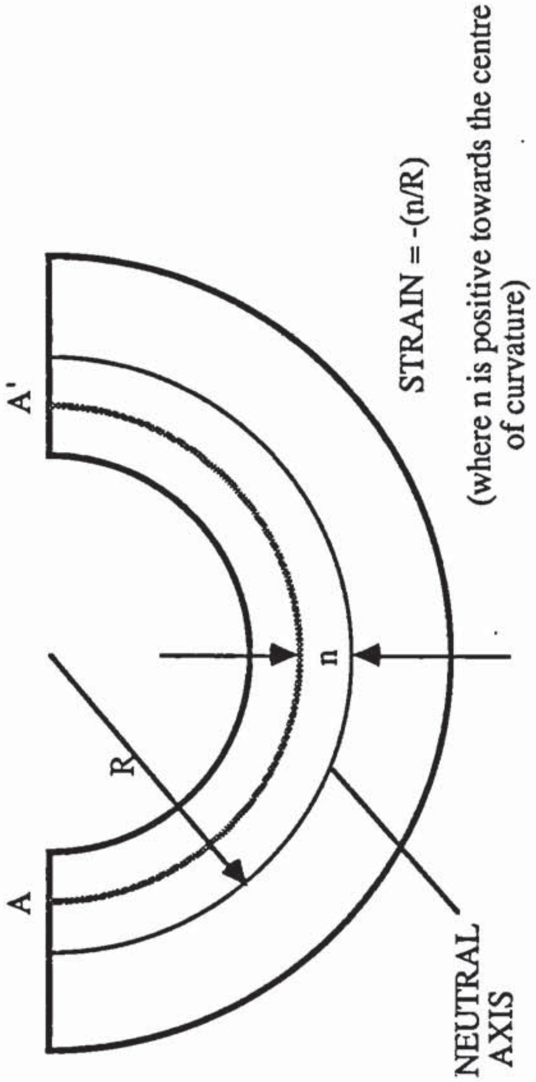


FIGURE 6.4 TRANSVERSE STRAIN IN BENDING

Other methods of estimating springback have been developed, Oh and Kobayashi[51] analysed the springback of metals in plane-strain sheet bending using the finite element method and, as would be expected, obtained considerably more detailed results concerning the shape of metal during bending and residual stresses and springback after. Levy[52] obtained equations for the springback of steels by using regression analysis techniques on sets of experimentally obtained values. The results of this approach of springback analysis are limited to the range of data from which they are derived. If the tool geometry or the material type are changed then further experimental testing is required. Since it is necessary to calculate springback prior to manufacturing tooling and purchasing material, statistical analysis is unsuitable for this application.

A further method of estimating springback is detailed below. It can be proved that (when Gardiners assumptions are made) the results are the same. Additionally, since the method is suitable for solution by numerical methods it has more potential than Gardiners equation.

Consider an element AA' (Figure 6.4) under bending before unloading, its original length,L, and final length,L', are as follows :

$$L=R\theta$$

and

$$L'=(R-n)\theta$$

where R is the radius to the neutral axis

n is the distance of the element from the neutral axis.

This gives the following expression.

$$\varepsilon_x=(L'-L)/L=(R\theta-n\theta-R\theta)/(R\theta)= -n/R \tag{8}$$

Figure 6.5 illustrates the strain distributions before unloading. The distribution of ε_x is shown in Figure 6.5A. Ordinarily ε_x will consist of two parts : plastic ε_x^p and elastic ε_x^e. Figure 6.5B shows the distribution of ε_x^e and Figure 6.5C the distribution of ε_x^p. Clearly, there will always be a region where the elastic limit is not reached, as the radius becomes smaller this area decreases and springback decreases.

Upon unloading springback occurs and the metal returns to some shape such as Figure 6.6. If the plastic state has been reached the metal cannot return to its original shape. The distribution of ε_x will still be governed by equation (8) where R is replaced by r. Where r>R. Therefore after unloading the distribution of ε_x is given by Figure 6.6A. The distribution of ε_x^p cannot change hence the distribution of ε_x^e is as described in Figure 6.6B.

Thus, whilst springback is the tendency of metal to return to its original shape and thus dissipate elastic energy, wherever permenant set occurs in the metal it is impossible to dissipate all of the elastic energy. It seems a reasonable assumption that the metal will springback to the radius which gives the minimum elastic energy. The best way to examine this statement is to make the same assumptions as Gardiner.

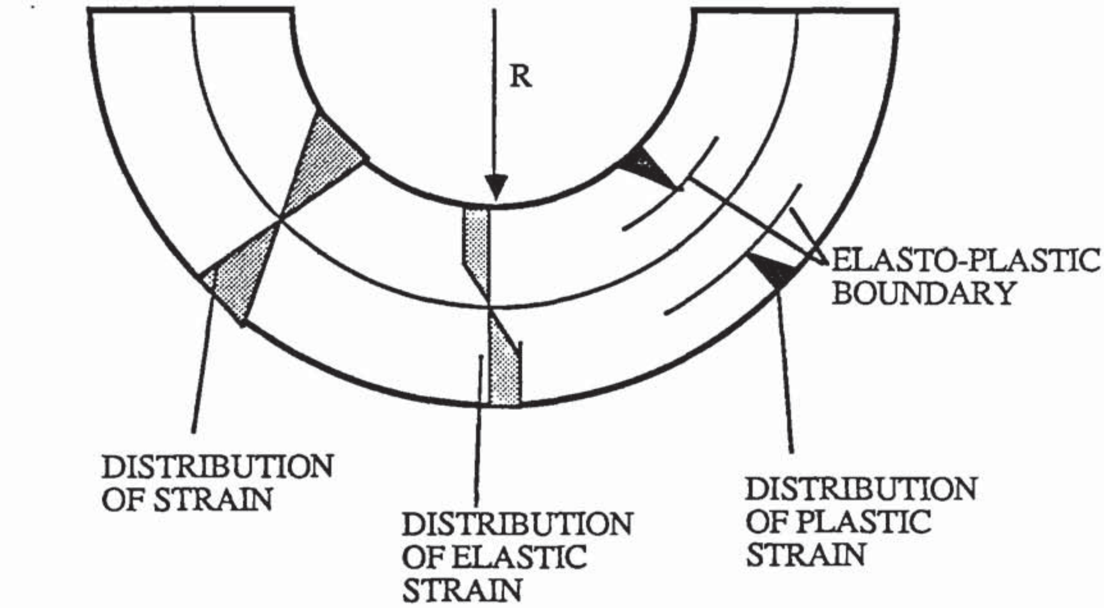
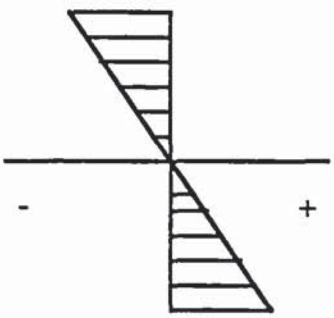
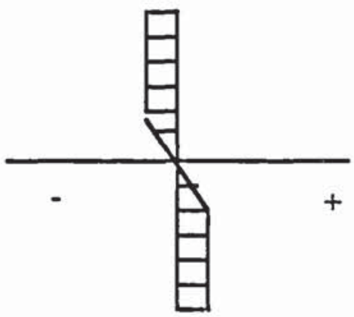


FIGURE 6.5 SPRINGBACK, THE STRAIN DISTRIBUTION PRIOR TO UNLOADING



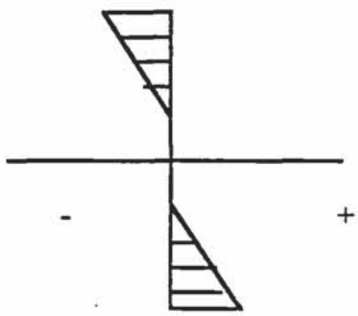
DISTRIBUTION OF STRAIN BEFORE UNLOADING

FIGURE 6.5A



DISTRIBUTION OF ELASTIC STRAIN BEFORE UNLOADING

FIGURE 6.5B



DISTRIBUTION OF PLASTIC STRAIN BEFORE UNLOADING

FIGURE 6.5C

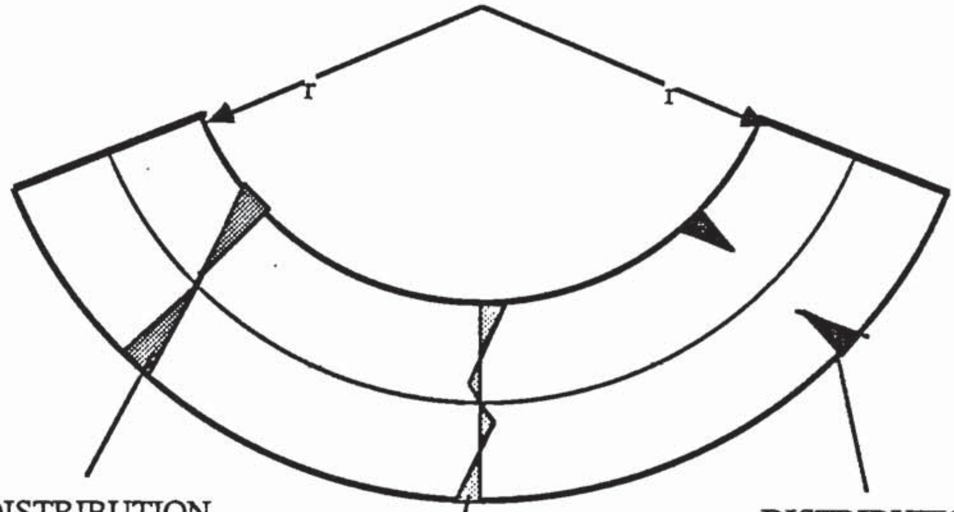
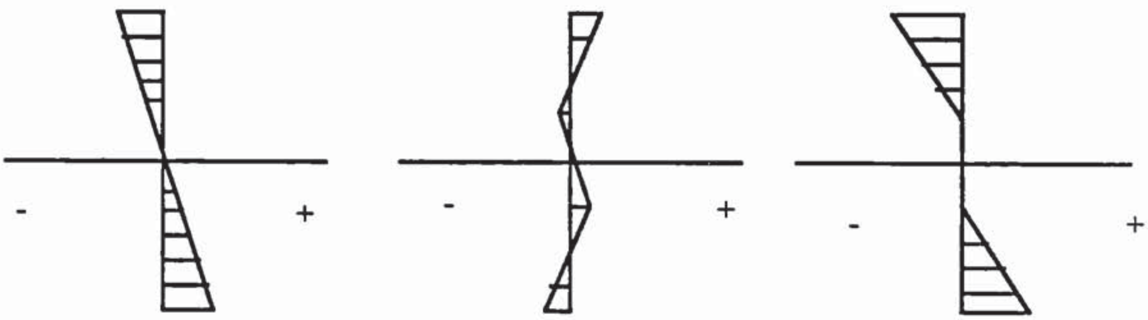


FIGURE 6.6 SPRINGBACK, THE STRAIN DISTRIBUTION AFTER UNLOADING



DISTRIBUTION OF STRAIN AFTER UNLOADING

FIGURE 6.6A

DISTRIBUTION OF ELASTIC STRAIN AFTER UNLOADING

FIGURE 6.6B

DISTRIBUTION OF PLASTIC STRAIN AFTER UNLOADING

FIGURE 6.6C

Namely :

(1) The neutral axis remains at the centre of the metal

(2) The material is elastic-perfectly plastic

(3) Conditions of plane strain exist.

(4) The strain is directly proportional to the distance from the neutral axis

(5) There is no stress at the neutral axis.

From (1) the distribution of ε_x is symmetrical about the neutral axis (although reversed in sign). Thus by minimising the elastic energy in one half of the metal thickness the total elastic energy is minimised.

Considering the outer (tensile) half of the metal with reference to Figure 6.5.

At a distance n from the neutral axis (since the outer half is below the neutral axix the signs are reversed), the strain, ε_x, can be expressed as follows :

Prior to unloading

$\varepsilon_x=(n)/R$ $\quad \varepsilon_x^e=n/R$ $\quad \varepsilon_x^p=0$ $\quad$ in the elastic region

and,

$\varepsilon_x=(n)/R$ $\quad \varepsilon_x^e=Y/E$ $\quad \varepsilon_x^p=(n/R)-(Y/E)$ $\quad$ in the plastic region

respectively.

After unloading

$\varepsilon_x=(n)/r \qquad \varepsilon_x^e=n/r \qquad \varepsilon_x^p=0$ in the elastic region

and,

$\varepsilon_x=(n)/r \qquad \varepsilon_x^e=\{(n/r)-[(n/R)-(Y/E)]\}$ in the plastic region

respectively.

Since yield occurs when $\varepsilon_x \geq Y/E$, the distance from the neutral axis of the elastic-plastic boundary is given by :

$n=(YR)/E$

Therefore after unloading

$$\varepsilon_x^e=\Big[n/r\Big]_{n=0}^{n=(YR)/E} \qquad \sigma=E\Big[n/r\Big]_{n=0}^{n=(YR)/E}$$

$$\varepsilon_x^e=\Big\{(n/r)-[(n/R)-(Y/E)]\Big\}_{n=(YR)/E}^{n=t/2} \qquad \sigma=E\Big\{(n/r)-[(n/R)-(Y/E)]\Big\}_{n=(YR)/E}^{n=t/2}$$

For a unit length the elastic energy (W)

$$W=(R\theta/2)\Big\{\int_0^{(RY)/E} E(n/r)^2\,dn+\int_{(RY)/E}^{t/2} E\{(n/r)-[(n/R)-(Y/E)]\}^2\,dn\Big\} \qquad (9)$$

Integration and rearrangement of equation (9) gives

$$W=(ER\theta/2)\Big\{[t^3/(24r^2)]-[t^3/(12rR)]+[(t^2y)/(4rE)]-[(RY)/E]^2[Y/(rE)]$$

$$+[2/(3rR)][(RY)/E]^3+\Big[[n^3/(3R^2)]-[(n^2Y)/(RE)]+[(Y^2n)/E^2]\Big]_{(RY)/E}^{(t/2)}\Big\} \quad (10)$$

For W to be a minimum, the differential of equation (10) with respect to r must be equal to zero, e.g.

$$\frac{d}{dr}\Big\{[t^3/(24r^2)]-[t^3/(12rR)]+[(t^2y)/(4rE)]-[(RY)/E]^2[Y/(rE)]$$

$$+[2/(3rR)][(RY)/E]^3+\Big[[n^3/(3R^2)]-[(n^2Y)/(RE)]+[(Y^2n)/E^2]\Big]_{(RY)/E}^{(t/2)}\Big\}=0$$

After differentiation and rearrangement this gives the following expression

$$(t^3/r)=(t^3/R)-[(3t^2Y)/E]+12R^2(Y/E)^3-(8/R)[(RY)/E]^3$$

Further rearrangement gives :

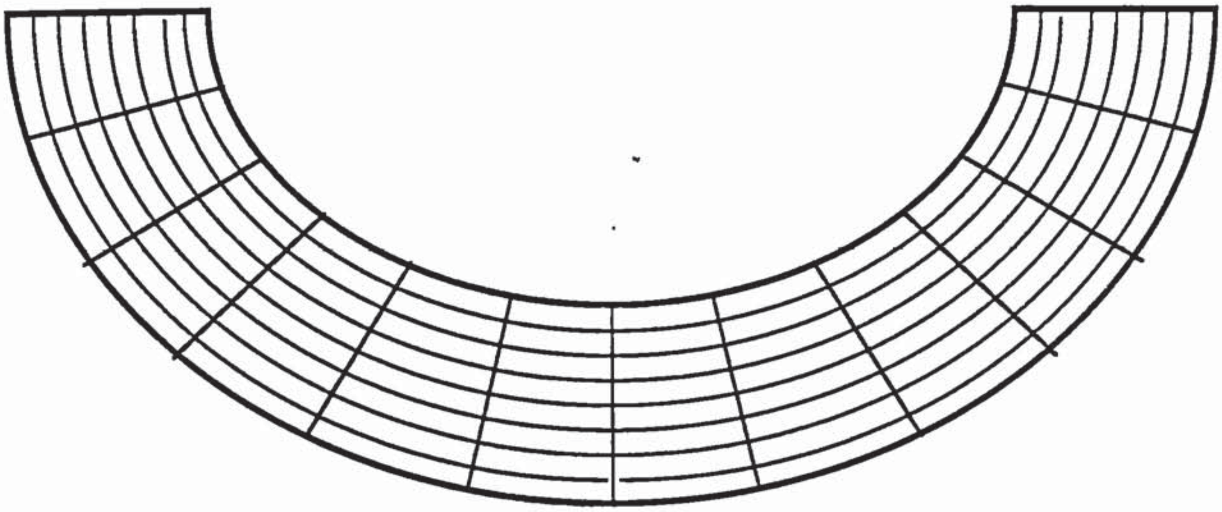
$$(R/r)=1-3[(RY)/(ET)]+12[(RY)/(ET)]^3-8[(RY)/(ET)]^3$$

which subsequently leads to :

$$(R/r)=1-3[(RY)/(ET)]+4[(RY)/(ET)]^3 \quad (11)$$

Thus it can be proved that the shape of metal which gives the minimum elastic energy is the same as the shape of metal which satisfies equilibrium, when the assumptions listed above are made. This has two important results.

(a) It is possible to calculate the radius after springback by a numeric method. By dividing the metal into a large number of elements (Figure 6.7) it is possible to numerically integrate the elastic energy. Thus by varying the radius after springback it is possible to calculate the radius which gives the minimum elastic energy.



THE BEND CAN BE SPLIT INTO A LARGE NUMBER OF ELEMENTS AND THE RADIUS WHICH MINIMISES ELASTIC ENERGY CALCULATED BY CONSIDERING THE ENERGY IN EACH ELEMENT.

FIGURE 6.7 NUMERIC METHOD OF CALCULATING SPRINGBACK

The advantage of this method is that it is possible to examine the springback when the simplifying assumptions are made more rigorous. For instance it is not necessary to assume the neutral axis is midway through the metal or that the strain is constant at any distance from the neutral axis or that the material is elastic perfectly plastic.

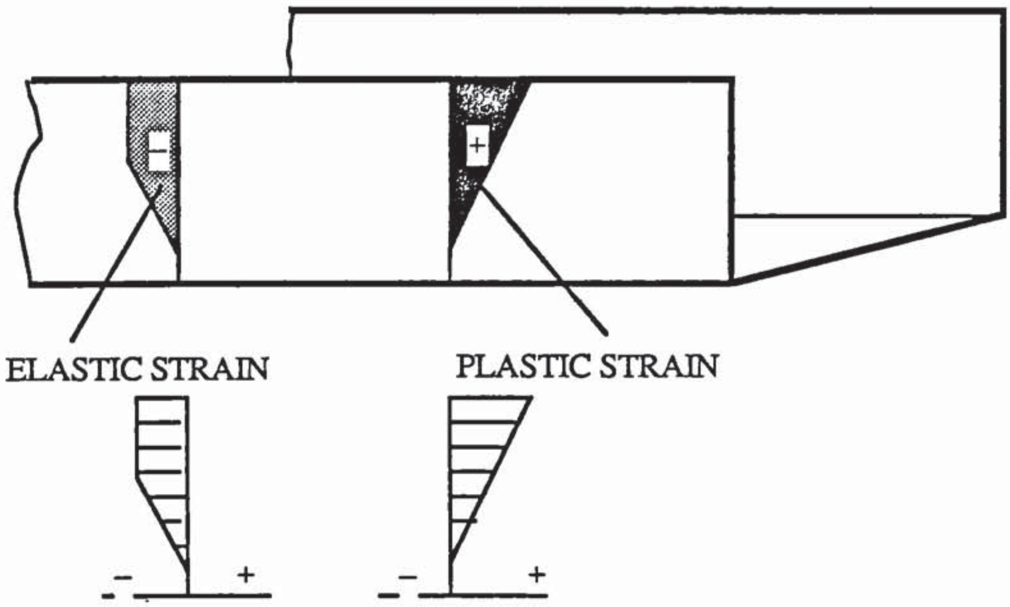
(b) The method has more potential in dealing with cold roll forming problems. Many cold roll forming defects can be seen as the materials tendency to dissipate elastic energy and achieve a state of minimum elastic energy.

For instance, when forming a symmetric channel a common problem is bow. This occurs when forming has been too severe and plastic straining occurs in the leg element. Figure 6.8 shows that when the channel adopts a curved shape the elastic strains decrease.

6.6.1 COMPUTER AIDED SPRINGBACK ANALYSIS

Section 4.4 described the means by which the metal springback is restricted and monitored using the automatic percentage composite element length option. Whilst this option should automatically decide the most suitable method of forming bends it was felt that the designer should have some graphical representation of the expected springback.

Thus, the springback estimation program has been developed, using the program the designer is asked for the material properties, yield stress and Young's modulus, and the geometric properties, inside radius, thickness and final bend angle, of the bend. The output can be either of a numeric or a graphical nature. Figure 6.9 shows the graphical output. The springback as the bend is formed up to and over the final angle is estimated by both Gardiners equation and the numeric minimum energy method described previously ,as would be expected the two curves are strikingly similar.



DURING THE ROLLING OF A CHANNEL SECTION THE SECTION MAY BECOME PLASTICALLY STRAINED LONGITUDINALLY. IF THE SECTION REMAINS 'STRAIGHT' ON LEAVING THE FINAL PASS.(I.E IN THE ABOVE DIAGRAM).AN OPPOSING ELASTIC STRAIN DISTRIBUTION WILL RESULT. HOWEVER IF THE SECTION ADOPTS A CURVED SHAPE, (I.E IN THE BELOW DIAGRAM),THE ELASTIC STRAIN BECOMES THE DIFFERENCE BETWEEN THE STRAIN DISTRIBUTION DUE TO BENDING AND THE PLASTIC STRAINING,AND HENCE IS REDUCED.

FIGURE 6.8 STRAIN DISTRIBUTIONS IN STRAIGHT AND CURVED CHANNEL SECTIONS

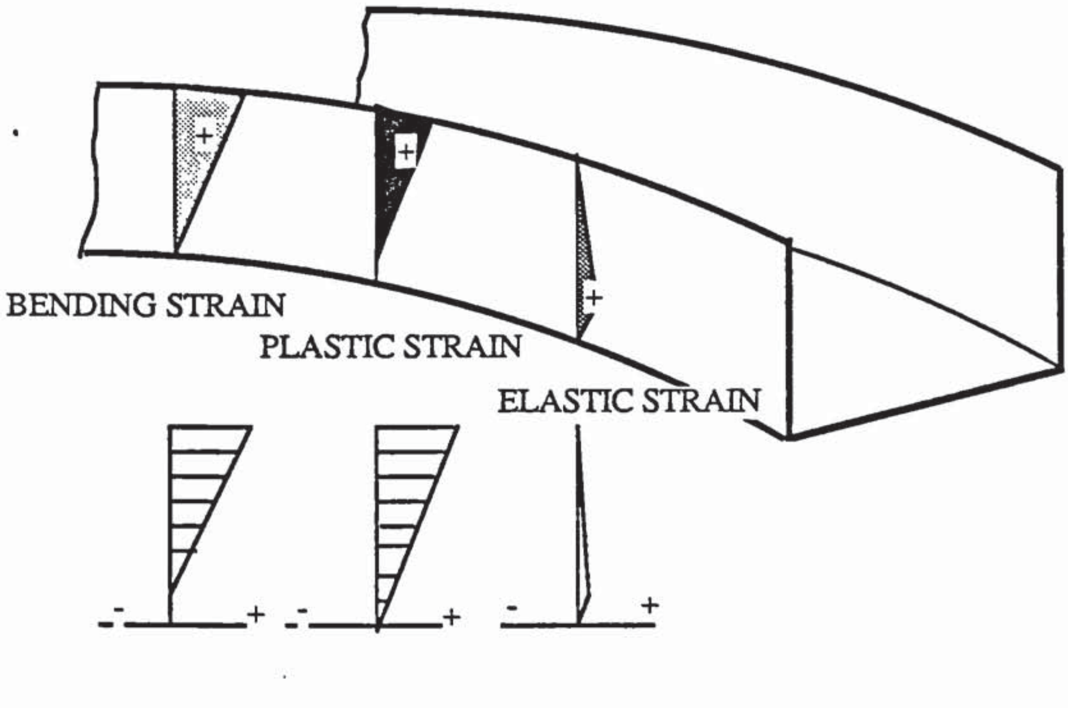
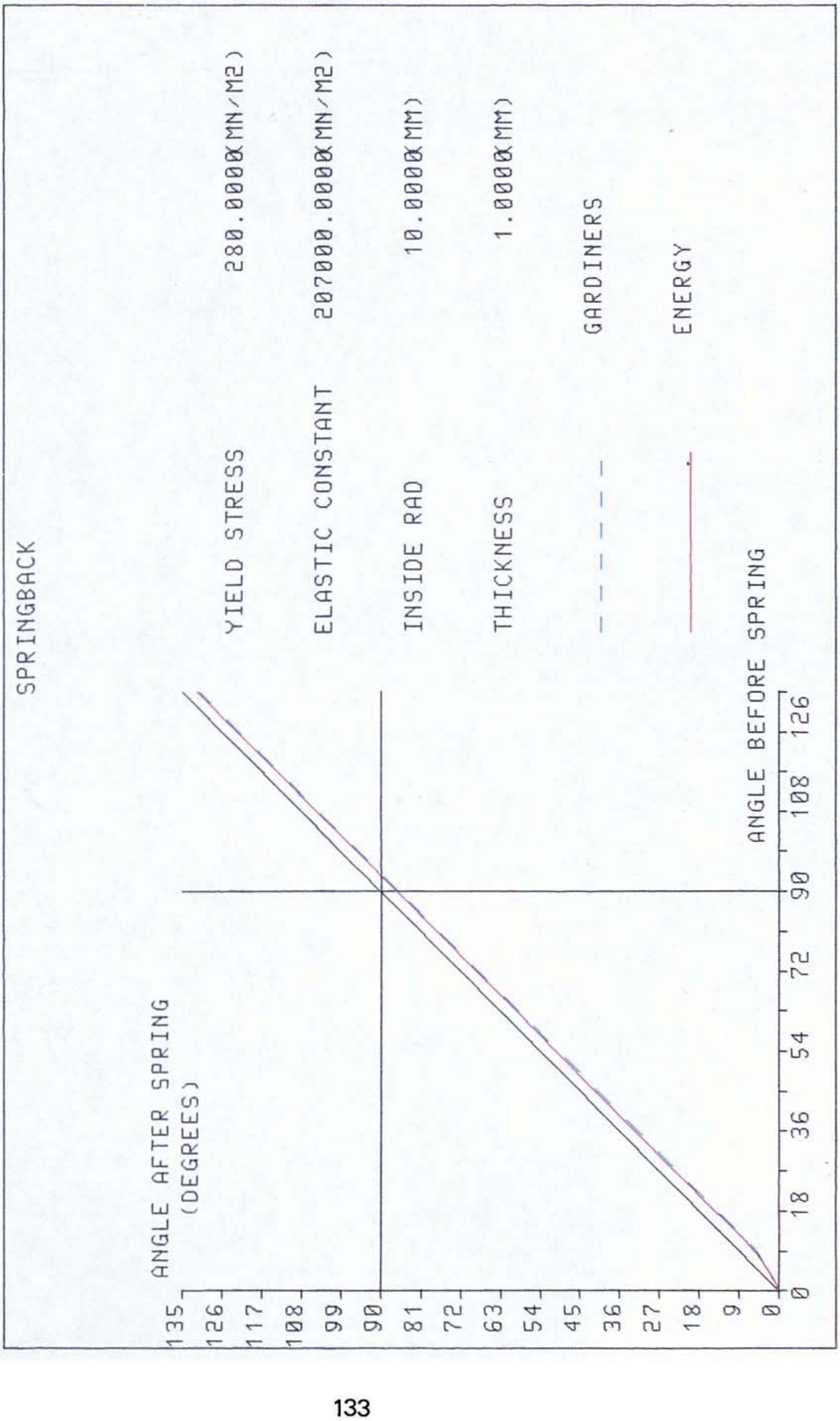


Figure 6.9 Graphical Representation of Springback



From diagrams such as Figure 6.9 the designer can visualise the general characteristics of the bends tendency to springback, also he can obtain specific information on the amount of overbend required and the first angle at which yielding will occur.

6.7 CONCLUSIONS ON THE EXPERIMENTAL AND THEORETICAL ANALYSIS OF FORM ROLL DESIGN.

From considering the experimental analysis of form roll design, the methods of theoretical analysis of metal deformation and the existing theoretical studies of cold roll forming the following can be noted. Whilst, experimental analysis will continue to be useful for the solution of specific section and process problems, it is unlikely that the guiding scientific principles required for consistently effective flower pattern will be derived solely from this source. Thus one must consider a combination of theoretical analysis and selective experimentation.

By noting the unusual properties of the cold roll forming process, it is obvious that any theoretical analysis of the cold roll forming process is going to be extremely complex. From a review of the means of theoretical analysis of metal deformation it can be seen that many methods can be discarded immediately and that the most promising method of metal forming analysis would seem to be using a minimum energy technique.

The most comprehensive theoretical study of cold roll forming appears to be the one performed by Kiuchi (primarily on tube rolling). This was detailed previously and is an impressive work based on the minimum energy technique, however it has a number of limitations which are discussed in section 6.4.

By considering the above, the approach adopted as being most suitable, was to numerically model the cold roll forming process using a minimum energy technique. Selective experimentation was also considered necessary as a basis for certain aspects of the numerical analysis and also as a means of assessing the validity of the model. Through a progression of modelling the process, performing selective experimentation, assessing the validity of the model and remodelling it is hoped that eventually a realistic model of the cold roll forming process will be developed. This will allow the designer to assess the form roll design at the design stage. A method by which the foll forming process can be modelled will be described in the following chapter.

CHAPTER 7

NUMERICAL ANALYSIS OF FORM ROLL DESIGN

7.1 INTRODUCTION

The previous chapters have mentioned the advantages that computer aided numerical analysis of form roll design can give the designer. In particular it is hoped to spot potential section defects at the design stage. This chapter will detail an initial attempt to model numerically the effect of form roll design. The model breaks down logically into a series of modules and the format of the chapter will reflect this with sections on:

(1) The control module
(2) The data input module
(3) Geometric definition of shape
(4) Derivation of strain from shape
(5) The rigid plastic option
(6) The stress distribution option
(7) Calculating power of deformation
(8) Minimising power
(9) Data output module

The chapter will also describe the construction and implementation of the model as a computer program and the means of executing the program. The philosophy in constructing the program has been to make the software as modular as possible so that individual components of the model logic can be easily altered without the need for rewriting the entire program.

7.2 THE CONTROL MODULE

As the name implies, the control module is the highest level in the model structure. It controls the sequence of application of the other modules, depending on the results of the variational module, and presets some values at the start of the program.

A summary of the control module logic is detailed in Figure 7.1 and clearly illustrates the stage by stage nature of cold roll forming where the final results from the previous stage form the input to the current stage.

7.3 DATA INPUT MODULE

The data required as input to the model can be considered under three categories, geometric data, material properties and mill properties. The purpose of the data input program is obviously to introduce all of the user defined variables into the program and pre-process these values when required.

The model is fully integrated into the Rolform CAD/CAM system. Therefore, the information defining the geometry of the metal at each stage is already contained in the 'D-file' and the 'F-file' and can thus be readily accessed by inputting the section number. The flower pattern information is then processed so that the state of each element is known at each stage.

The model also requires information defining the material properties of the metal being rolled; Young's modulus, yield stress, Poisson's ratio and the strain hardening rate. The purpose of providing the material properties is in deriving the stress field from the strain field if the elastic-plastic option is chosen. The designer is given the option of treating the problem as plane stress .

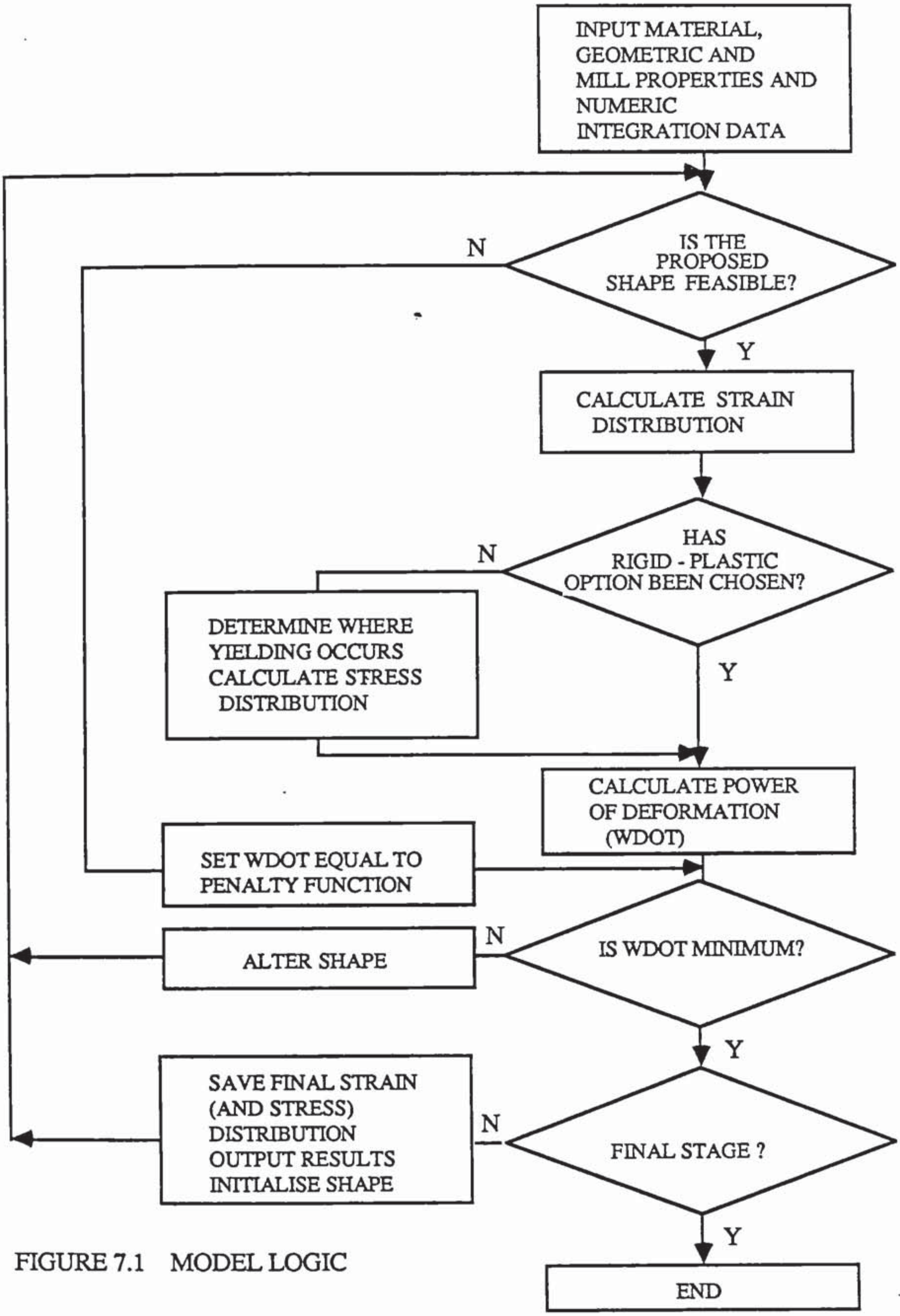


FIGURE 7.1 MODEL LOGIC

The third set of variables, are those defining the rolling mill and the dimensions of the rolls used. For each pass the pass length, the pass height and the pass centre to centre distance are input . Finally the rolling velocity is input.

Since the model takes a considerable time to run fully, the opportunity is given to stop and restart the program at any stage in the process. When restarting at a stage other than the first, then the variational data is asked for which defines the preceding stages.

7.4 GEOMETRIC DEFINITION OF SHAPE

If the rolling of a section was stopped whilst metal was still in the mill, the metal which had been deformed from flat strip but had not yet reached the finished section shape would be referred to as being the tag. At the points corresponding to the centre lines of the rolls a cross section through the metal should of course be the same as the template profile. A cross section through the metal at any other point would given an unknown profile and the overall three dimensional shape of the metal would be extremely complex. The branch of mathematics which deals with the approximation of surface shape by numerical means is large and complex , and one which is particular relevant to computer aided design (see for instance Gardan[53] or De Fages De Casteljau[54] for recent accounts of developments in this area).

This leads to a major problem, then, in that realistically approximating the metal shape requires many parameters, and since there is a large range of possible shapes, ideally power should be minimised with respect to all of these parameters. However, maintaining the computing time to perform the simulation at a reasonable level is a continuous problem and, since the time taken to minimise a function can be said to be roughly proportional to the number of variables squared, it is imperative that the number of variables controlling shape must be kept to a minimum.

Thus, it is expedient to make simplifying assumptions as to the nature of the shape of metal, in order to restrict the range of possible shapes and thus restrict the number of dependent variables in the modelled shape. In the previous chapter it was shown that Kiuchi restricted the number of independent variables to one. This would seem to be unrealistic, particularly where more than one bend is "active" at one time. With two active bends, it is possible that the distribution of bending will be quite evenly distributed through one of the bends and highly unevenly distributed over the other, with the shape factor described in the previous chapter it would be impossible to model such a shape, thus for the general case it was decided to have at least one variable for each active bend at each pass. The advantage, then, of modelling the metal shape by this method is that, whilst one has to make simplifying assumptions as to the cross sectional shape of the linear and circular elements between passes, more complex sections can be approximated.

What is required, then, is a function which is sufficiently flexible to reasonably model the range of distributions of bending which can be expected, with the minimum number of parameters. The function must also satisfy the following conditions.

$$\theta = S\theta \text{ AT } y=0$$

$$(1)$$

$$\theta = F\theta \text{ AT } y=L$$

where: y is the distance from the preceding pass.

L is the distance between two successive passes (the pass length).

θ is the angle of bending at a distance y from the preceding pass.

$S\theta$ is the angle of bending at the preceding pass.

$F\theta$ is the angle of bending at the end of the pass.

EQN (1) is satisfied by the equation

$$\theta = S\theta + (F\theta - S\theta)\, S(y)$$

$$\begin{aligned} &\text{if } S(y) = 0 \text{ AT } y = 0 \\ &\text{and } S(y) = 1 \text{ AT } y = L \end{aligned} \qquad (2)$$

The function S(y) will be referred to as the shape factor. The best method of determining the most suitable shape factor is by comparison of possible shape factors with experimental data. Thus prior to implementing the model as a computer program the bending angle distributions were obtained for two complete sections, (a total of eleven passes).

The first section chosen was an angle section (Figure 7.2),rolled in HR3 steel , with a total of 5 passes (Figure 7.3). The second section chosen was a channel section (Figure 7.4), rolled in galvanized steel ,with a total of 6 passes (Figure 7.5). It was known that because of the widely differing thicknesses the two sections would exhibit widely disparate bending distributions and thus test the versatility of any proposed shape factor. With each section, the mill was stopped, the rolls removed and the sectional tags lifted out. Plate 7.1 shows the tag of section 1 , plate 7.2 shows the tag of section 1 in the region of the rolls.

Having obtained the tags, the bending distributions were obtained by the following method. For the first section, since the section was relatively thick, springback was not going to be a significant problem. Thus, it was possible to remove specimen strips of metal from the tag at various points along its length. These specimens were then examined on a Nikon model 5A shadowgraph from which the angle of bending could be easily obtained.

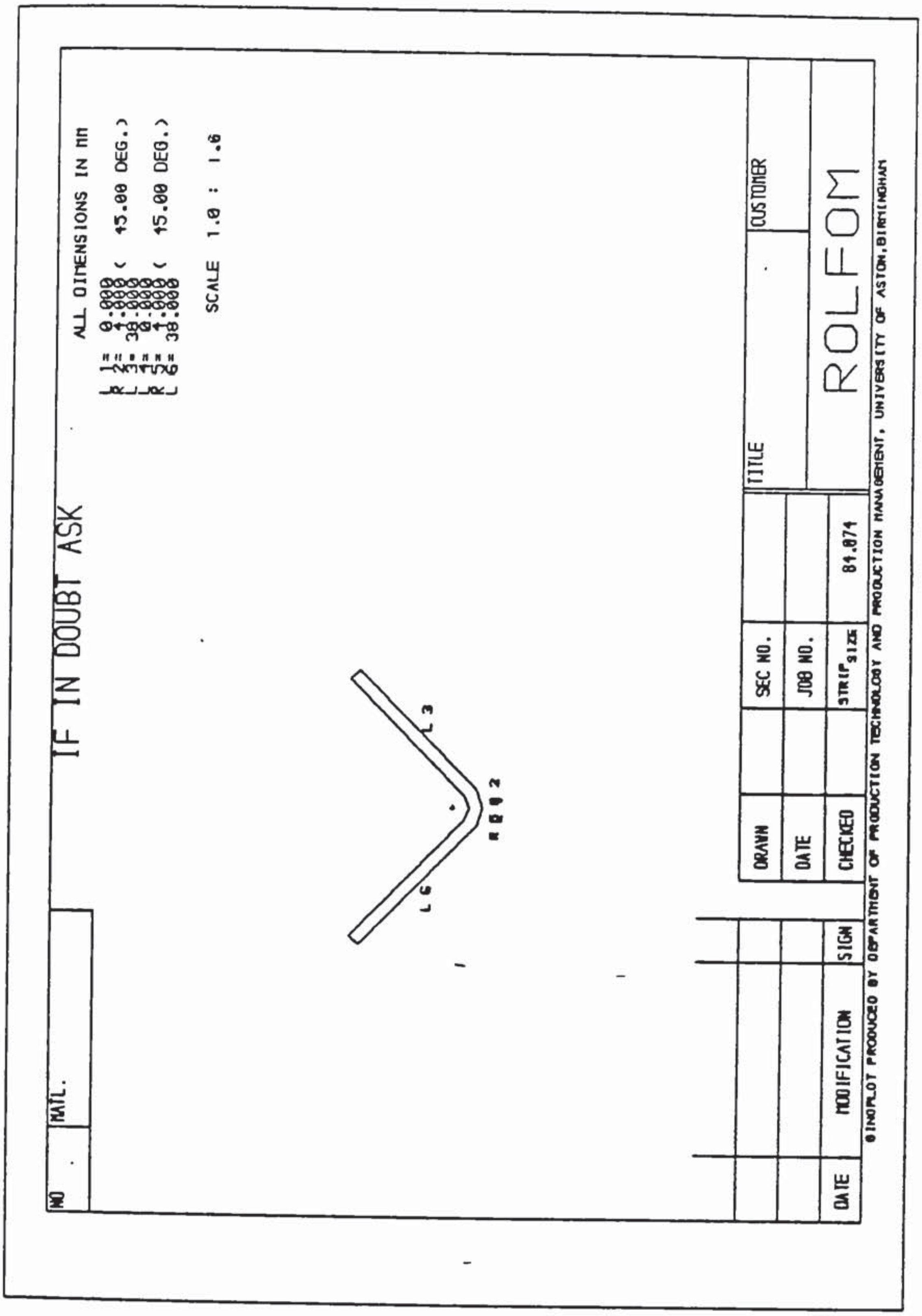


FIGURE 7.2 ANGLE SECTION

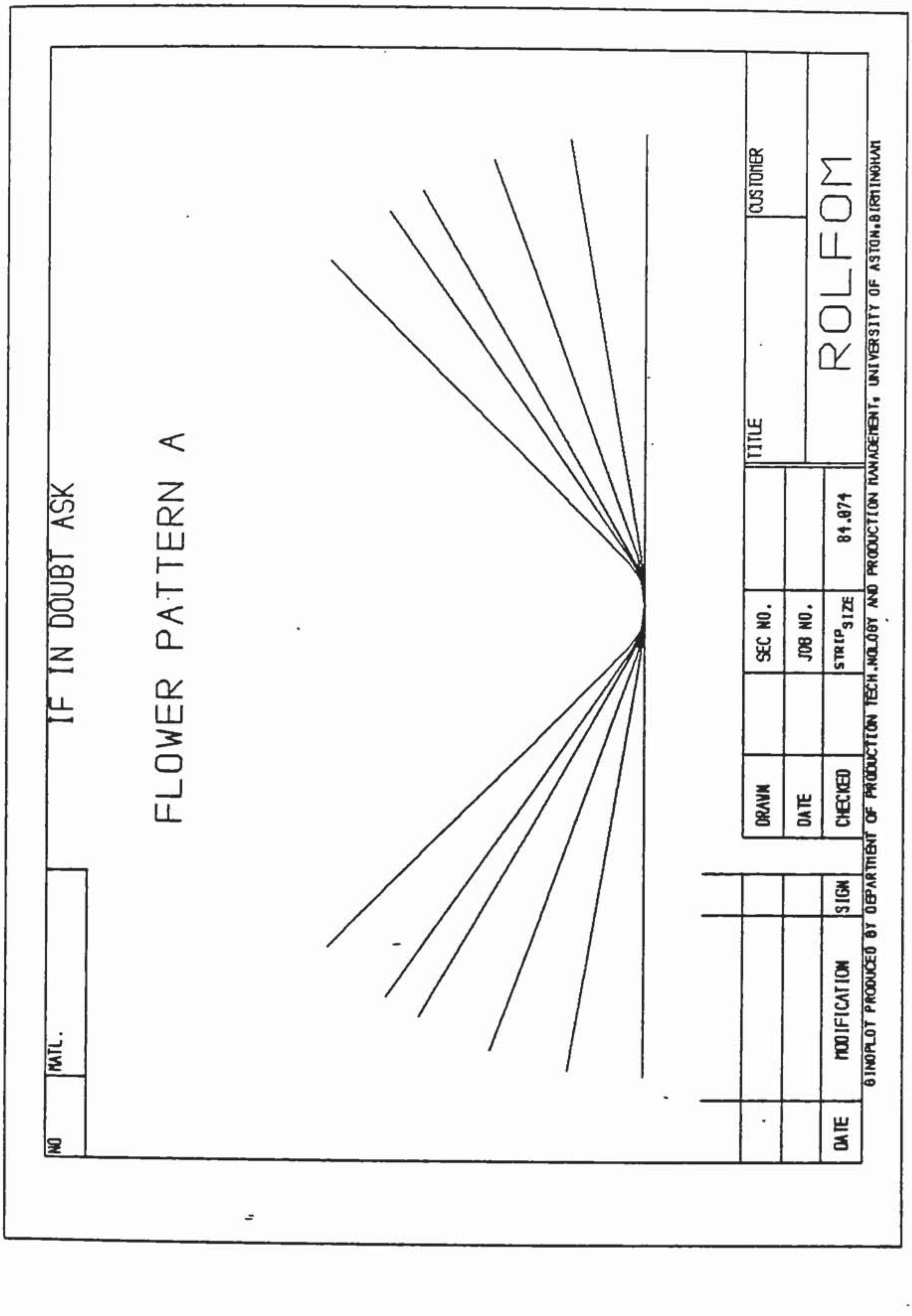


FIGURE 7.3 ANGLE SECTION FLOWER PATTERN

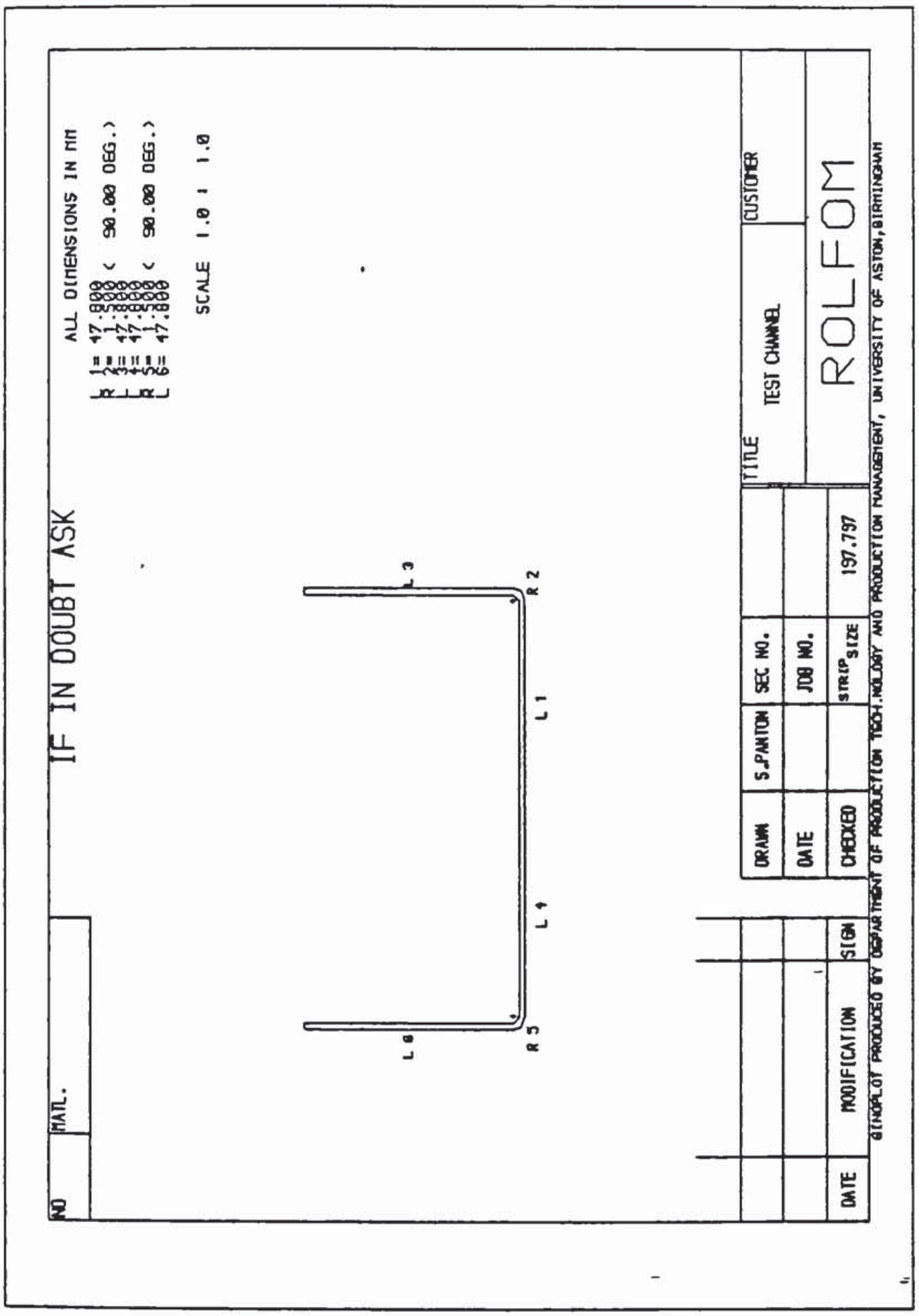


FIGURE 7.4 CHANNEL SECTION

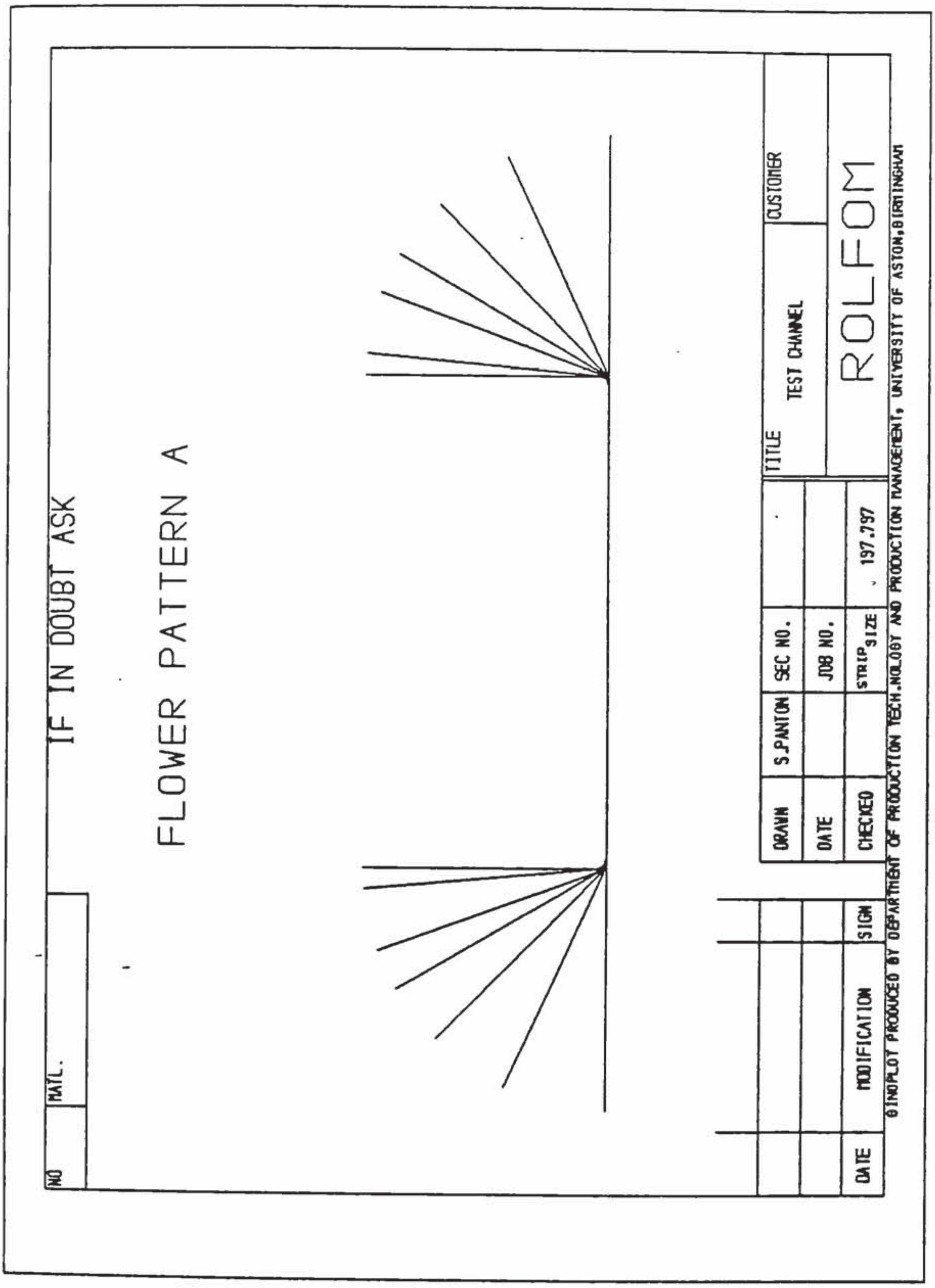


FIGURE 7.5 CHANNEL SECTION FLOWER PATTERN

PLATE 7.1

DEFORMED SPECIMEN OF ANGLE SECTION

PLATE 7.2

DEFORMED SPECIMEN IN THE REGION OF THE ROLLS

For the second section the above method could not be adopted since the strip was far thinner, thus the angle of bending was measured using a Moore and Wright precision protractor. Having obtained the bending distributions for each pass they were converted into a dimensionless format. (AN' and Y')

$$AN' = (\theta - S\theta) / (F\theta - S\theta)$$
$$y' = y / L \qquad (3)$$

AN' and y' are in the range 0 - 1.The curves obtained by plotting AN' against y' were then compared with a variety of potential shape factors satisfying eqn (2). Of these potential shape factors two were chosen to form options in the model.

$$S(y)=\mathrm{Sin}[(\pi/2)(y/L)^n] \qquad (4)$$

$$S(y)=e^{-a[(L-y)/y]^b} \qquad (5)$$

Where n, a and b are variables.

The reasons for the choice of these two functions are given below. Equation (5) was selected since it was noted that this function appeared to most accurately reflect the experimentally obtained bending distributions. This can be seen in Figure 7.6 ,which shows the distribution of bending of section 1 with a representative family of curves provided by eqn (5), the general shapes of the experimental and theoretical curves can be seen to be of a similar appearance. By considering the distribution of bending for a particular pass (Figure 7.7), the shape factor can be seen to closely follow the experimental curve. Figure 7.8 shows the distribution of bending of section 2 with a representative family of curves provided by equation (5). Thus,by considering Figures 7.6 - 7.8 it can be seen that, by varying a and b, equation (5) can reasonably approximate two widely disparate distributions of bending.

Figure 7.6 Distribution of bending comparison between angle section and exponential shape factor.

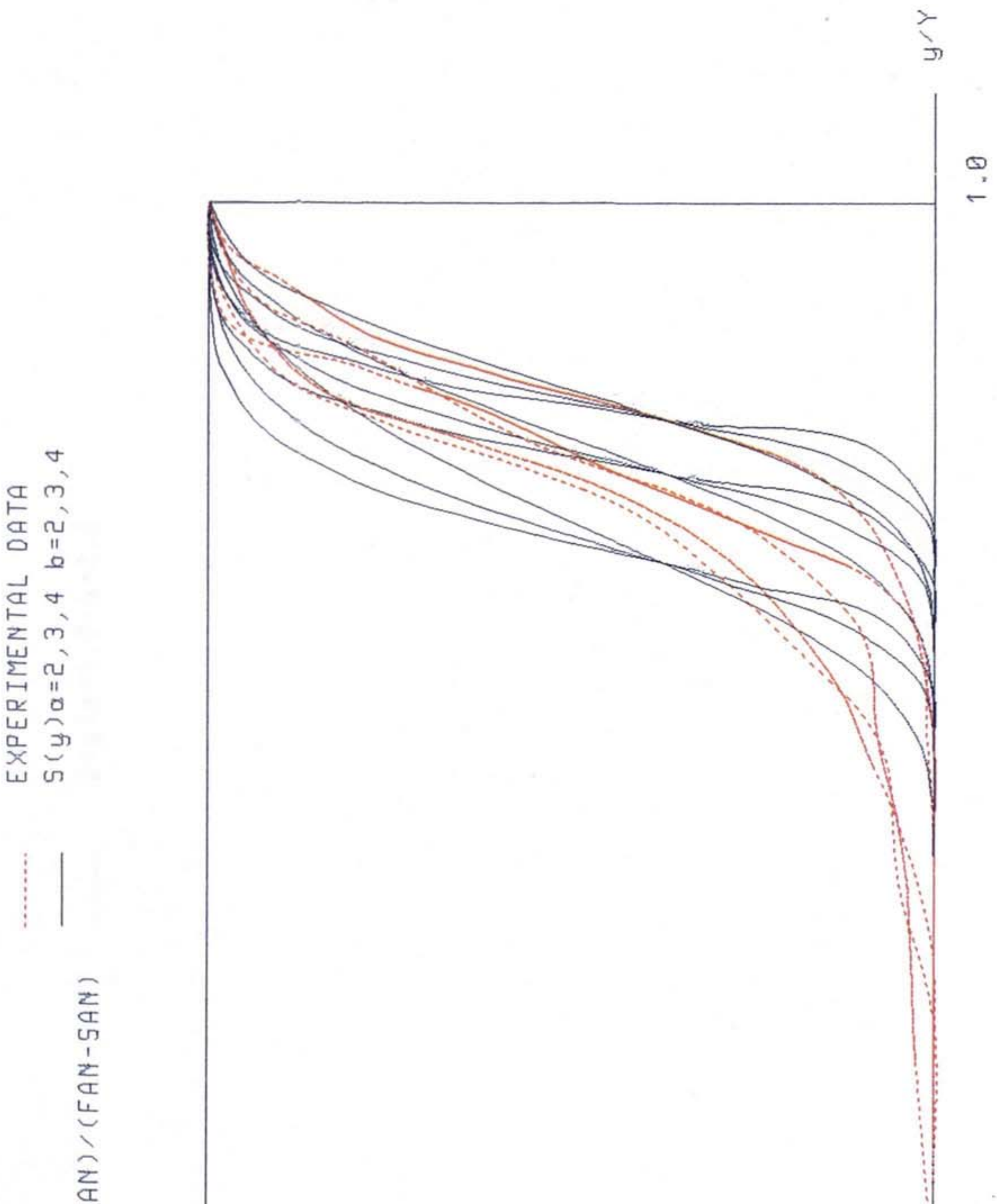


Figure 7.7 Distribution of bending : comparison between single pass and exponential shape factor.

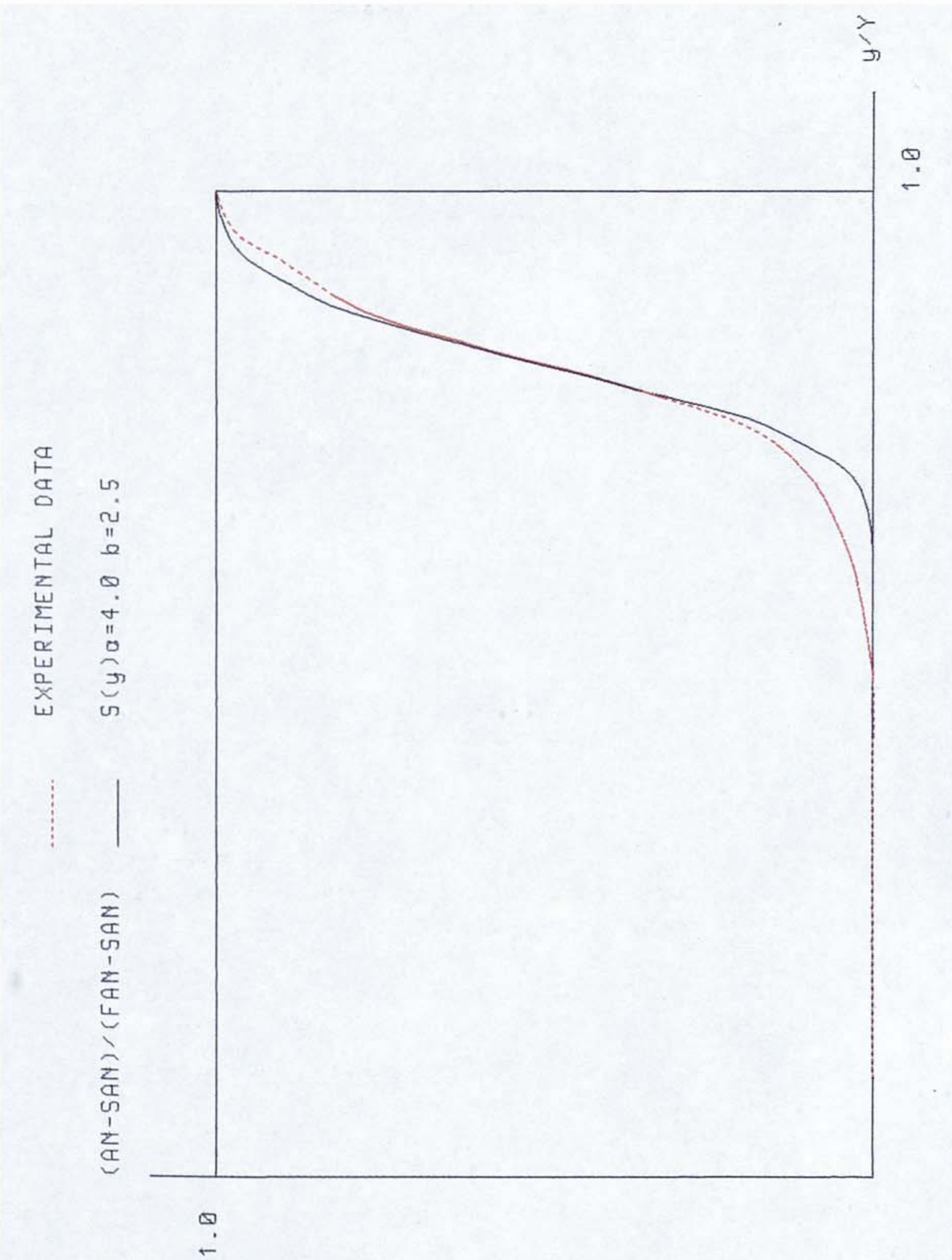


Figure 7.8 Distribution of bending : comparison between channel section and exponential shape factor.

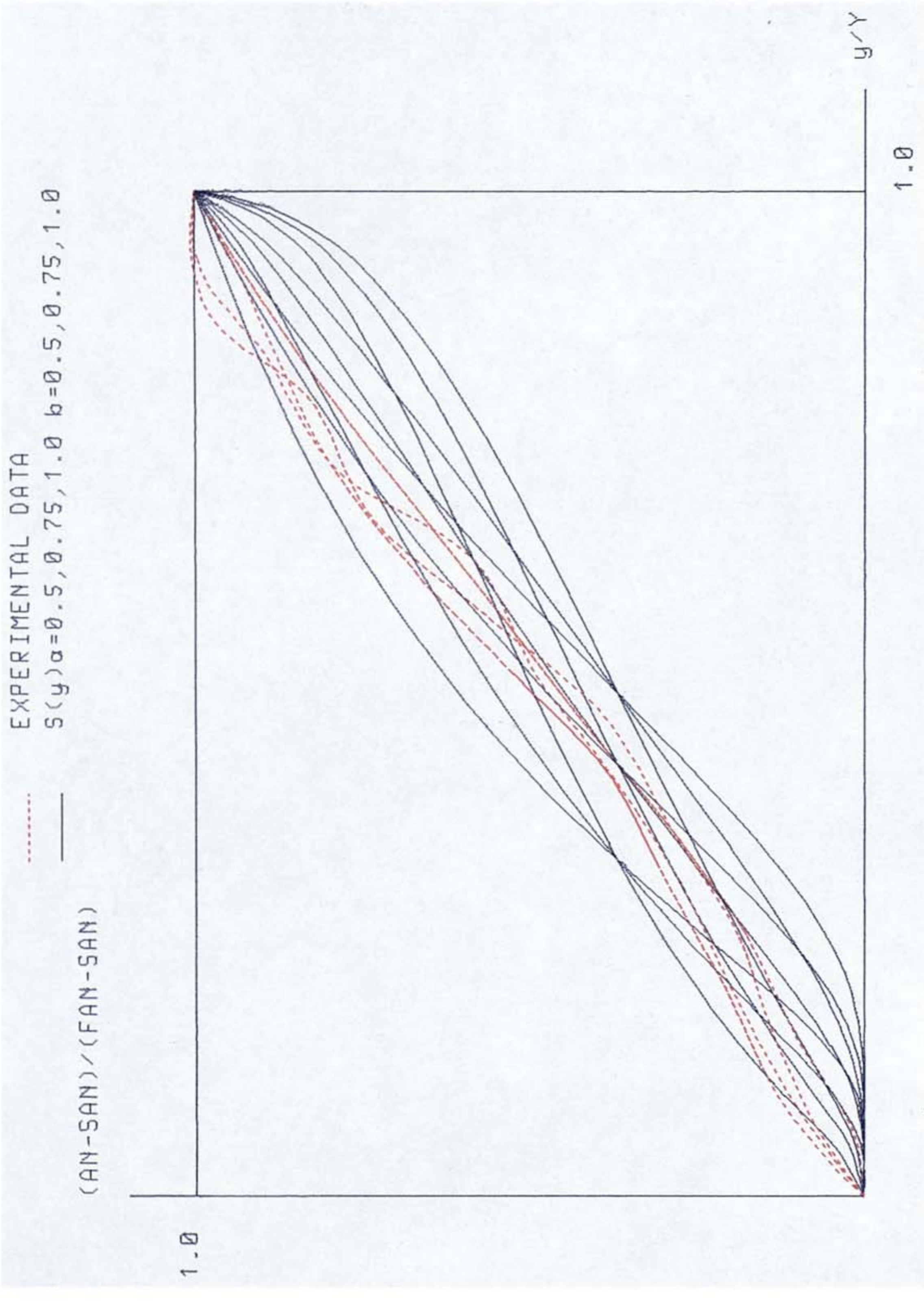
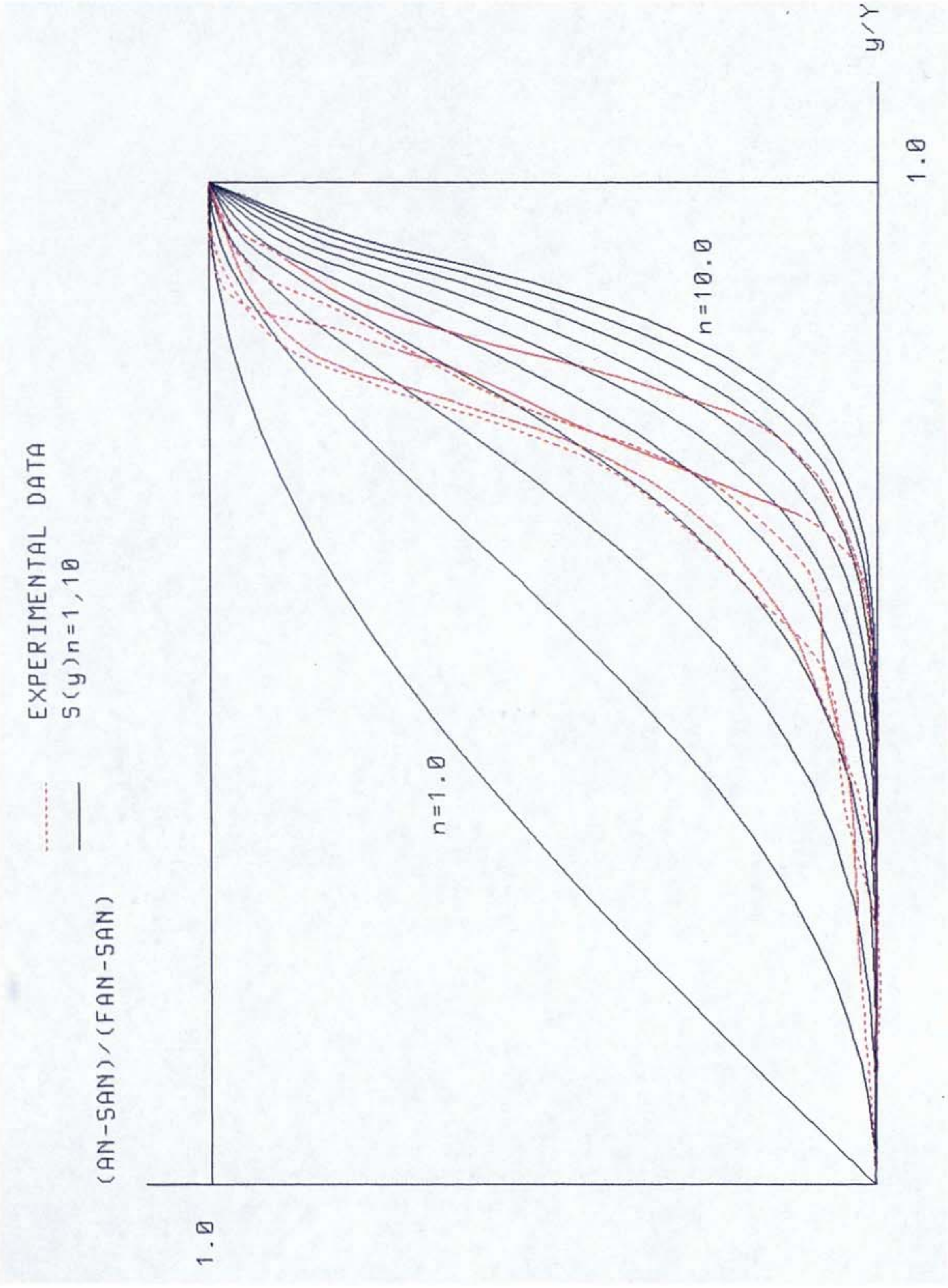


Figure 7.9 Distribution of bending : comparison between angle section and sinusoidal shape factor.



Equation (4) was chosen since, whilst it does not follow the experimental data as closely as equation (5) (Figure 7.9), it provides an answer in approximately 25% of the time necessary when using equation (5). Also ,since as the variable n increases the severity of forming increases ,it is easier to visualise the effect which altering parameters has on the severity of forming.

7.5 DERIVING THE STRAIN FIELD

Strain is, of course, a non-dimensional statement of the deformation of an object and is commonly expressed as being the ratio of elongation to original length. An alternative statement is true strain, the natural logarithm of length divided by original length. The first, more familiar, value is used throughout when strain is referred to.

The previous section detailed the numeric means of defining the geometry of the metal shape between passes, the present section is concerned with the assumptions made in deriving a strain field and the means of deriving a strain field from any proposed metal shape. Clearly, as with shape, it is important that the assumptions defining the strain field are as realistic as possible, within the constraints imposed by the complexity of the process and the computing power available.

Figure 7.10 details the relative orientation of the two sets of axes referred to later in the section. The axes XYZ are relative to the centre line of the flower pattern and are thus constant over the entire pass. The axes xyz are relative to the nominal neutral axis of the metal at any point in the strip. Thus, the xy plane defines the nominal neutral axis of the pass and the relative orientation of xyz and XYZ will alter between any two points in the pass. Where the terms transverse, longitudinal and thickness are used they refer to the x,y and z axes respectively.

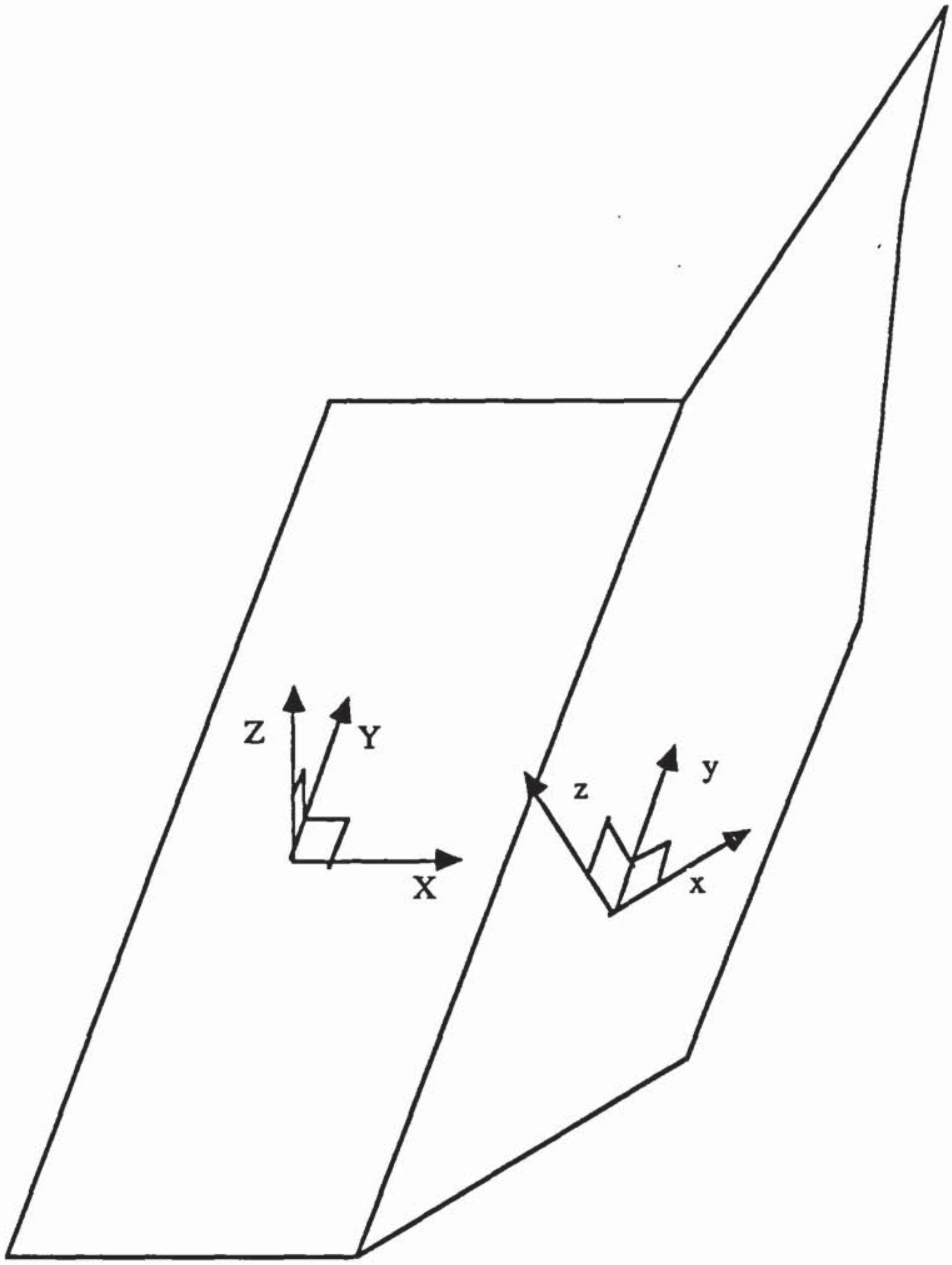


FIGURE 7.10 RELATIVE ORIENTATION OF AXES

In the modelling of the cold roll forming process, deformation from two sources are considered. Firstly, the deformation demanded by the formation of the bends which define the metal shape is considered. Secondly, the deformation caused by the metal movement demanded by the tooling geometry is included. Whilst the first form of deformation is often numerically far larger than the second, it is known that the metal movement required by the flower pattern is a major factor in the propogation of section defects and thus must be included in the study.

It is perhaps illuminating to detail what is meant by the deformation caused by the requirements of metal movement. Considering Figure 7.11, a diagram of one stage in the roll forming of a channel, in bending from 30 degrees to 45 degrees a point on the edge of the section moves a distance D in the XY plane. Therefore the distance AA' must be greater than the distance BB' and hence straining must occur. It is tempting to say, (as Gradous[55] did) that :

$$\text{Longitudinal strain.} = \left(\sqrt{(L^2+D^2)} - L\right) / L \qquad (6)$$

However it is known from practical observation, (see for instance Sarantidis[18]), that deformation is not evenly distributed throughout the pass but is concentrated in the latter stages. Hence, considering Figure 7.12 , a more appropriate method is to divide the pass incrementally and to apply the above equation on a smaller scale, and thus develop a strain field over the whole of the pass.

7.5.1 ASSUMPTIONS IN DERIVING THE STRAIN FIELD

The following assumptions are made in deriving the strain distribution for a proposed shape.

(I) The principal strains are coincident with the x,y and z axes.

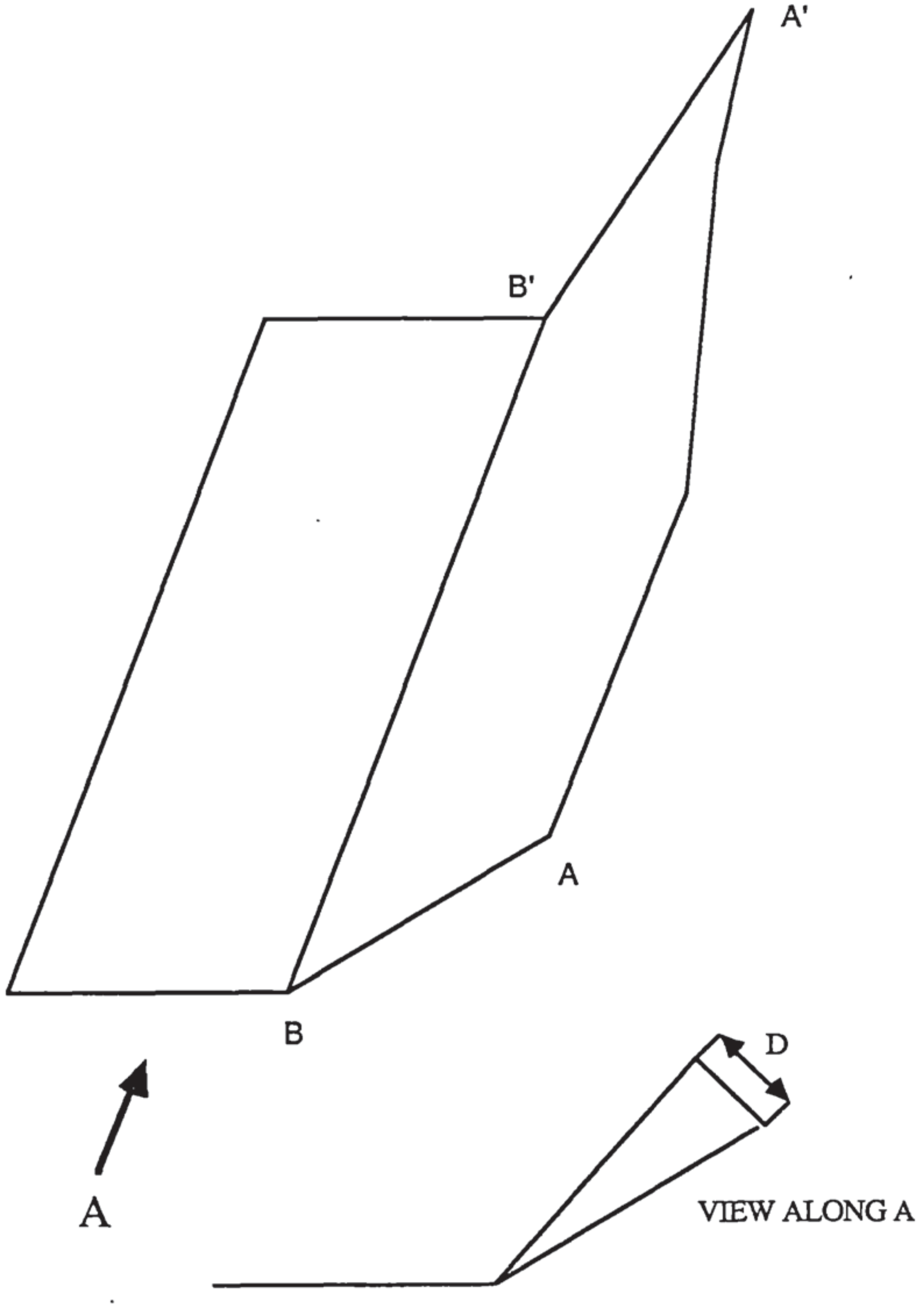


FIGURE 7.11 LONGITUDINAL STRAINING IN A CHANNEL SECTION

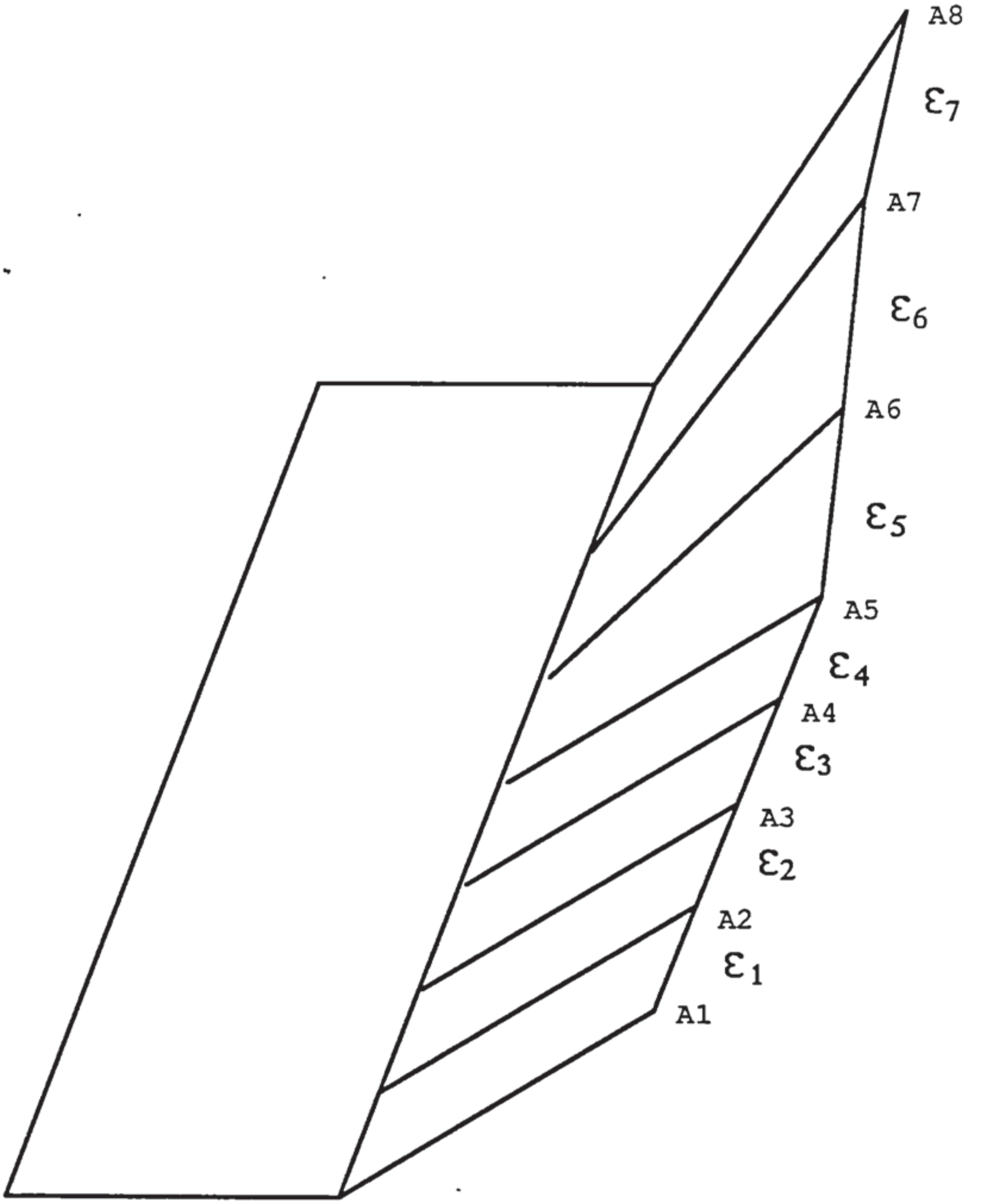


FIGURE 7.12 LONGITUDINAL STRAINING IN A CHANNEL SECTION

(II) The metal remains plane and perpendicular as it moves through the rolls. That is, a section through the strip prior to deformation defined by y = 0 will remain defined by y= constant at any time in the cold roll forming process.

(III) The sum of the principal strains is zero.

(IV) In the circular elements the transverse straining is zero midway through the thickness.

(V) In the circular elements the transverse strain is directly proportional to the distance from the neutral axis.

(VI) In the linear elements the stress in the thickness direction is neglible and is treated as zero.

Assumptions (I) and (II) are necessary to simplify the formulation to a manageable level. As such they occur regularly in the analysis of many metal forming processes. Assumption (III) , that the sum of the principal strains is zero, assures that volume constancy is maintained throughout the process, which is a condition of the upper bound theory. This assumption neglects elastic compressibility and assumes that the product of two strains is negligibly small. Again these are necessary to simplify the model into a manageable form. Assumptions (IV) and (V) are standard simplifications in the analysis of bending (see for instance Appendix B, the derivation of Gardiner's equation). Since in the linear elements the thickness is constant, there are no forces out of the xy plane acting on the element and the thickness is small compared to the other dimensions the thickness stress is negligibly small and considered zero.

7.5.2 DERIVATION OF LONGITUDINAL STRAIN

With reference to Figure 7.13, considering an element of original length dY at a distance Y from the downstream pass, in moving from Y to Y+dY there are movements dX, dZ required by the metal movement demanded by the process.

$$\text{The longitudinal strain } \varepsilon_y = \{[\sqrt{(dX^2+dY^2+dZ^2)}]-dY\}/dY \qquad (7)$$

The values dX, dZ are the sums of the movements of the elements towards the centre of the section and the movement of the element itself. Take, for instance the case of a channel, consider the movement of a point on the linear section, (with reference to Figure 7.14).

$$dX=\delta X_1+\delta X_2 \qquad dZ=\delta Z_1+\delta Z_2 \qquad (8)$$

Thus in general for a point on the n^{th} element

$$dX_n=\sum_{i=1}^{i=n} \delta X_i$$

$$dZ_n=\sum_{i=1}^{i=n} \delta Z_i \qquad (9)$$

In order to develop a general algorithm for determining dX and dZ it is necessary to first identify and define all the possible distinct cases of metal movement. With reference to Figure 7.15 it can be seen that for the general case there are six distinct possibilities,namely:

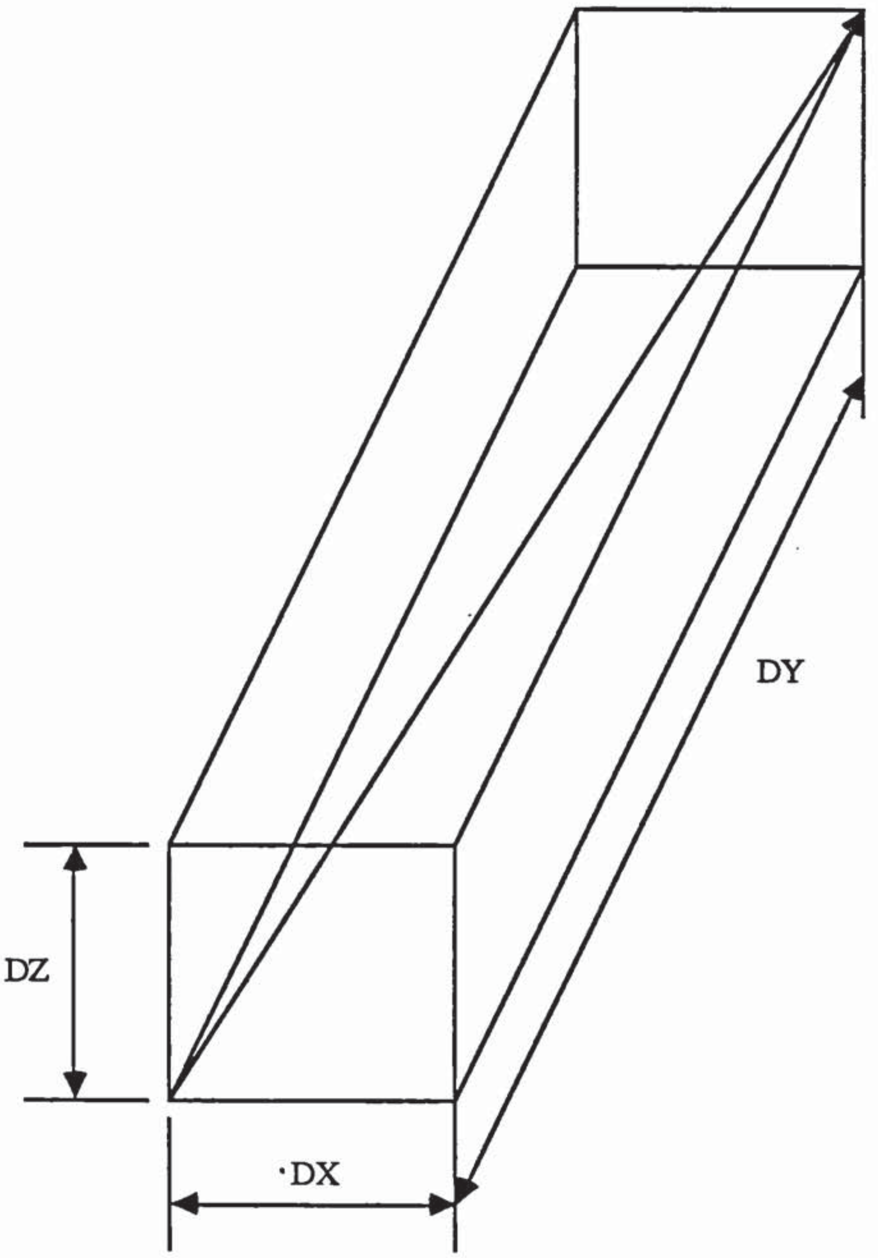
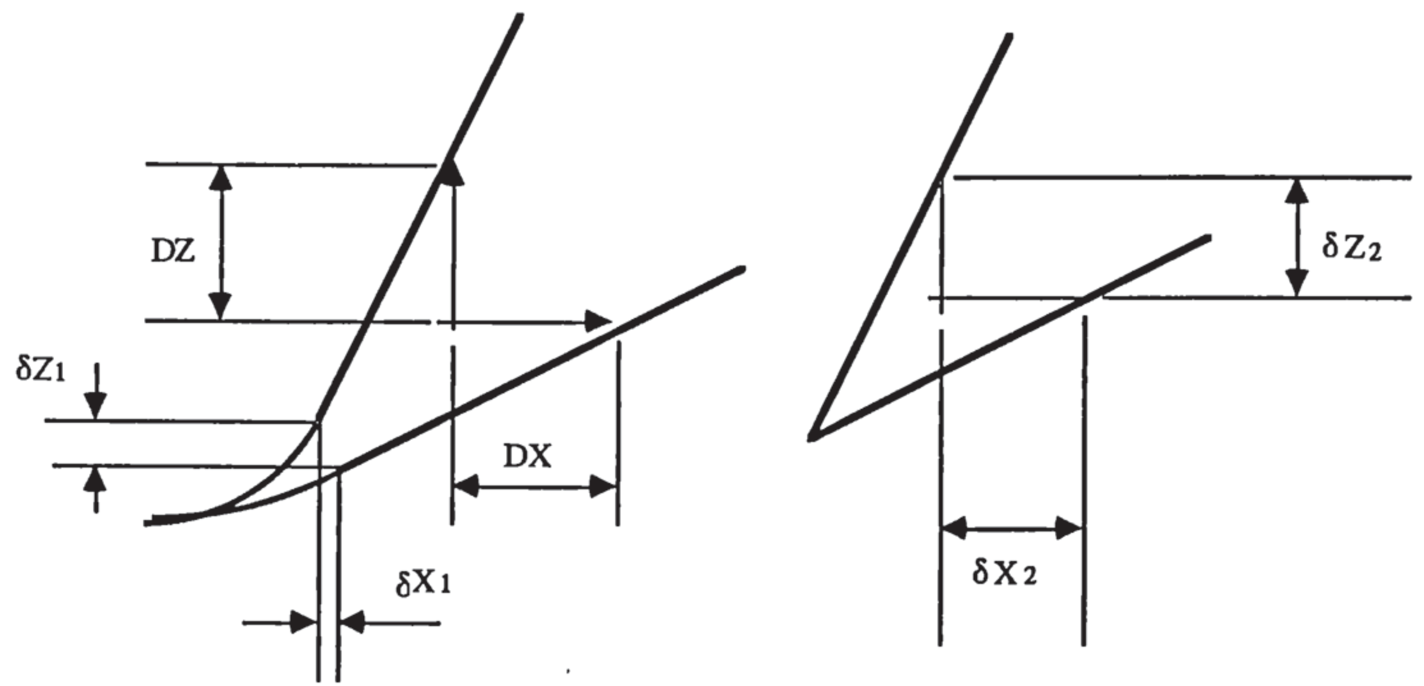


FIGURE 7.13 COMPONENTS OF LONGITUDINAL STRAIN



$$DX = \delta X_1 + \delta X_2$$

$$DZ = \delta Z_1 + \delta Z_2$$

FIGURE 7.14 DETERMINING INCREMENTAL METAL MOVEMENTS

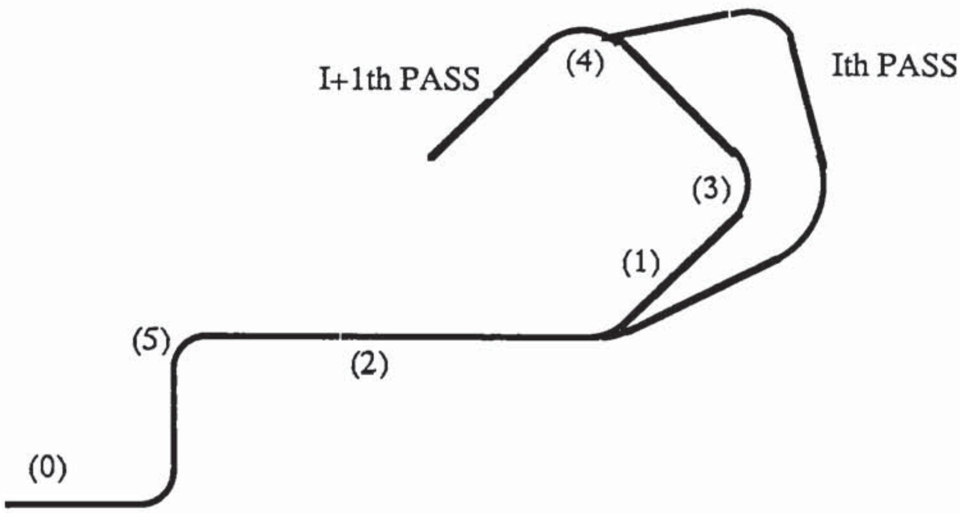


FIGURE 7.15 EXAMPLES OF ELEMENT TYPES

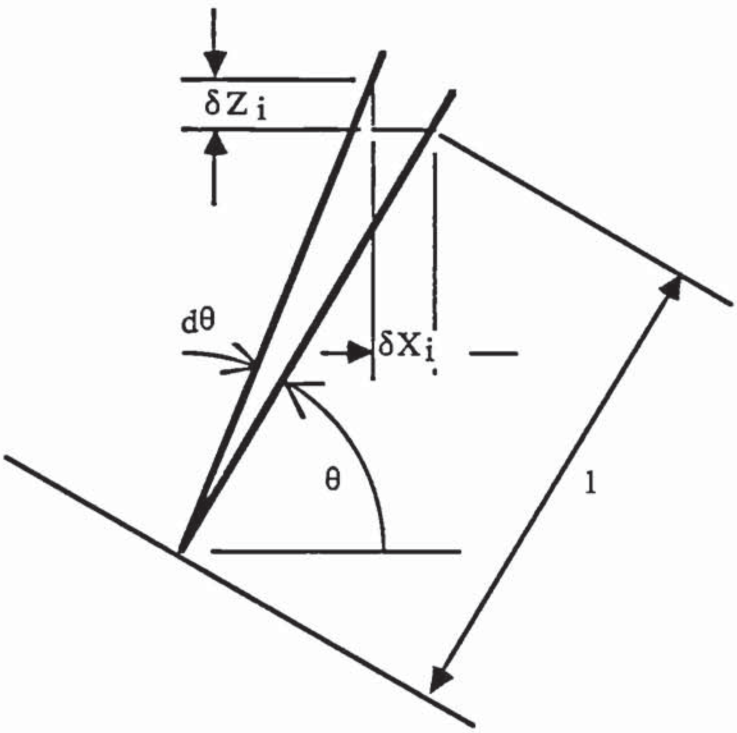


FIGURE 7.16 CASE NUMBER 1

Case 0 Linear element with no metal movement

Case 1 Linear element with metal movement

Case 2 Circular element, being bent, with no preceding circular elements being bent

Case 3 Circular element, being bent, with preceding circular element being bent.

Case 4 Circular element, not being bent, with preceding circular element being bent.

Case 5 Circular element, not being bent, with no preceding circular element being bent.

CASE 1 :

With reference to Figure 7.16

l is the distance from the junction of the linear element with the preceding element

θ is the angle of inclination of the linear element at a distance Y from the preceding pass

$\theta+d\theta$ is the angle of inclination of the linear element at a distance Y+dY from the preceding pass

$$dX_i=[l\cos(\theta+d\theta)]-l\cos(\theta)$$

$$dZ_i=[l\sin(\theta+d\theta)]-l\sin(\theta) \tag{10}$$

where θ and $\theta+d\theta$ are defined by the shape factor

FIGURE 7.17 CASE NUMBER 2

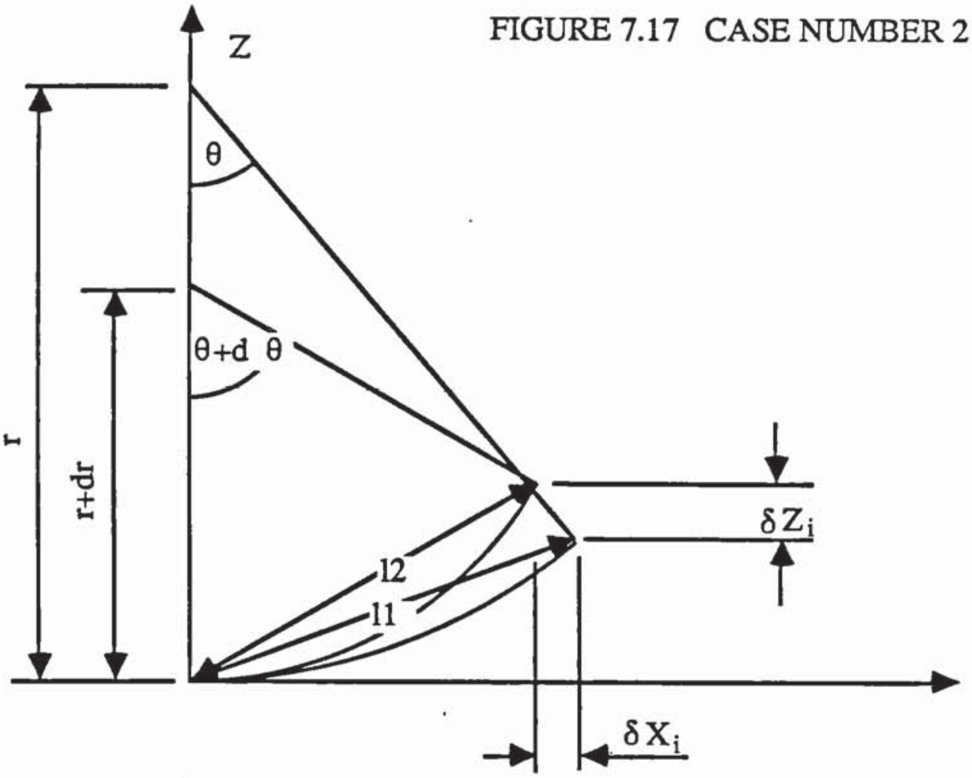
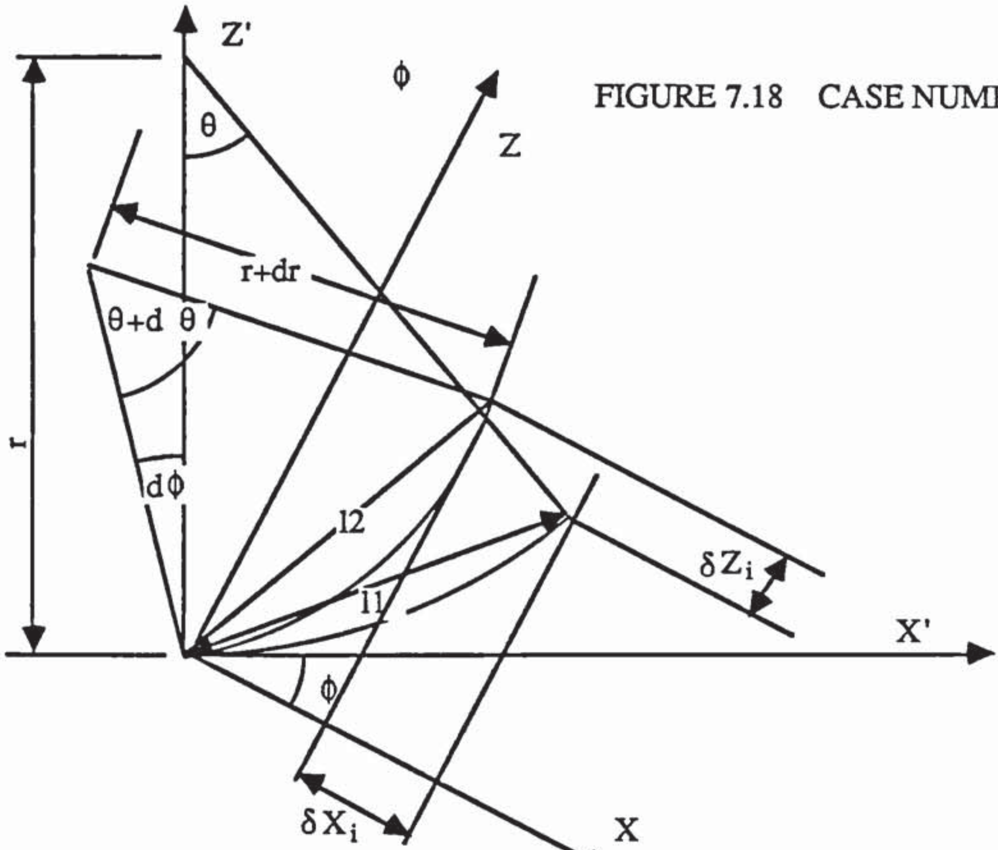


FIGURE 7.18 CASE NUMBER 3



CASE 2 :

With reference to Figure 7.17

θ is the bend angle of a point on the circular element at a distance y from the preceding pass

$\theta+d\theta$ is the bend angle of a point on the circular element at a distance y+dy from the preceding pass

r if the radius at a distance Y from the preceding pass

r+dr is the radius at a distance Y+dY from the preceding pass

$$l_1=2r\sin(\theta/2)$$

$$l_2=2(r+dr)\sin[(\theta+d\theta)/2]$$

$$\delta X_i=l_2\cos[(\theta+d\theta)/2]-l_1\cos(\theta/2) \qquad (11)$$

$$\delta Z_i=l_2\sin[(\theta+d\theta)/2]-l_1\sin(\theta/2)$$

where θ, r, $\theta+d\theta$,r+dr can be obtained from the shape factor.

CASE 3 :

With reference to Figure 7.18

θ is the angle of bending of a point on the circular element at a distance Y from the preceding pass

$\theta+d\theta$ is the angle of bending of a point on the circular element at a distance Y+dY from the preceding pass r is the radius at a distance Y from the preceding pass

r+dr is the radius at a distance Y+dY from the preceding pass

φ is the angle of inclination of the preceding element at a distance Y from the preceding pass

$\varphi+d\varphi$ is the angle of inclination of the preceding element at a distance Y+dY from the preceding pass

$$l_1 = 2r\sin(\theta/2)$$

$$l_2 = 2(r+dr)\sin[(\theta+d\theta)/2]$$

$$\delta X_i = l_2\cos\{[(\theta+d\theta)/2]+\varphi+d\varphi\}-l_1\cos[(\theta/2)+\varphi] \qquad (12)$$

$$\delta Z_i = l_2\sin\{[(\theta+d\theta)/2]+\varphi+d\varphi\}-l_1\sin[(\theta/2)+\varphi]$$

CASE 4 :

Case 4 is similar to Case 3 where dr,dθ=0

$$l= l_1 = l_2 = 2r\sin(\theta/2)$$

$$\delta X_i = l\cos\{[(\theta)/2]+\varphi+d\varphi\}-l\cos[(\theta/2)+\varphi] \qquad (13)$$

$$\delta Z_i = l\sin\{[(\theta)/2]+\varphi+d\varphi\}-l\sin[(\theta/2)+\varphi]$$

7.5.3. TRANSVERSE AND THICKNESS STRAINING IN THE CIRCULAR ELEMENT

Consider a fibre AA' in the circular element shown in Figure 7.19.

where r is the radius to the neutral axis

n is the distance of AA' from the neutral axis (positive towards centre of curvature)

θ is the angle of bending

Original length AA'=r θ

Final length AA'=(r-n) θ

Therefore ,the transverse strain, $(\varepsilon_x) = \{[(r-n)\ \theta]-r\ \theta\}/(r\ \theta) = -n/r$ (14)

Since it has been assumed that the sum of the principal strains is zero, it is possible to obtain the thickness straining, (where the longitudinal straining has been derived in section 7.5.2 and the transverse straining has been derived above), since

$$\varepsilon_z = -(\varepsilon_x + \varepsilon_y) \qquad (15)$$

7.5.4 TRANSVERSE AND THICKNESS STRAINING IN THE LINEAR ELEMENT

The longitudinal straining in the linear element has been detailed in section 7.5.2. It remains to obtain expressions for the transverse and thickness strains, it is possible to

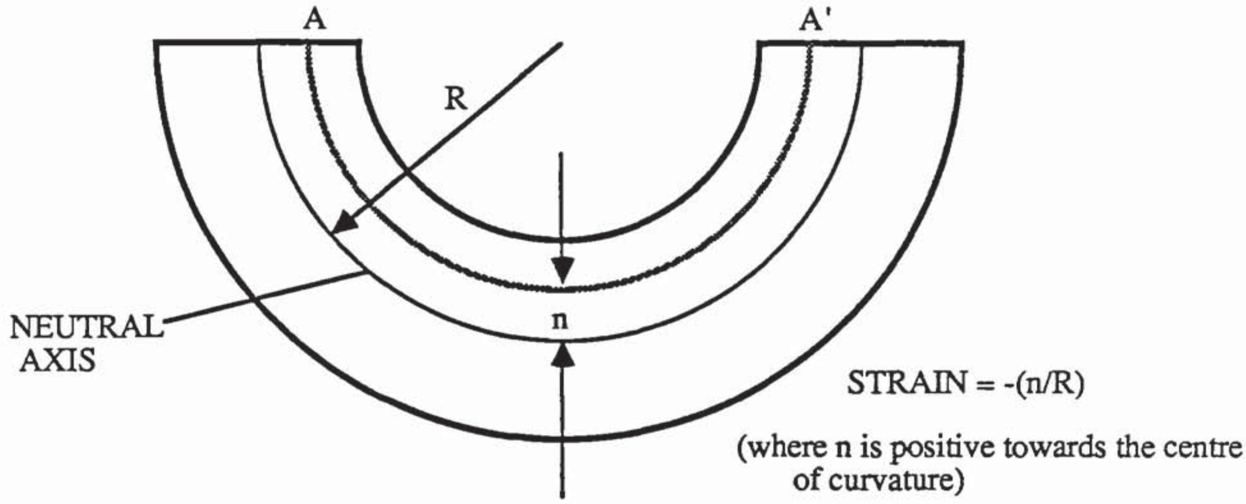


FIGURE 7.19 TRANSVERSE STRAIN IN BENDING

obtain a relationship between the remaining principal strains from the earlier assumption that the sum of the principal strains should be zero. Also , since the thickness is constant , there are no forces out of the xy plane acting on the element and the thickness is small compared to the other dimensions the thickness stress can be considered as zero. These two conditions are satisfied simultaneously by the relationship.

The ratio $\varepsilon_x : \varepsilon_y : \varepsilon_z$ is $-1 : 1 : 0$ (16)

It can be seen that this relationship satisfies the condition that the sum of the principal strains is zero. It is also shown that the relationship will always give a thickness stress of zero, for the proposed method of determining stress, in appendix C. Moreover , the relationship is in accordance with what is expected of the cold roll forming process, that the thickness remains constant.

7.6 THE STRESS STRAIN RELATIONSHIP

Previous sections have dealt with the geometric definition of shape and the derivation of a proposed strain field. The following section will detail the stress strain relationship. In general, to fully define the stress strain relationship requires a statement of the relationship between stress and strain within the elastic region, a statement of the relationship between stress and strain in the plastic region and a statement of the yield criteria. With the model the designer chooses from two options.

(I) The rigid plastic option

(II) The elasto-plastic option

7.6.1 THE RIGID PLASTIC OPTION

Using the minimum energy approach it is usual to assume a rigid plastic formulation , such that the equivalent stress can be considered constant. For example , Bhattacharyya[48] assumed the material was rigid plastic in the analysis of channel sections. The principal advantage of assuming the material is rigid plastic, in this case, is that the computing time is greatly reduced (by around 50%), where the magnitude of the computing time is an important concern.

7.6.2 THE ELASTO-PLASTIC OPTION

Whilst the rigid plastic option has the advantage of reducing the computing time , it has been shown that at least one common section defect, springback, is caused by the dissipation of elastic energy. Also, it is suspected that many other section defects are the result of the dissipation of elastic energy . Furthermore, it should be remembered that the objective of the model is to provide the information for assessing potential section defects at the design stage. The model, then, must eventually contain the ability to obtain the stress distribution by considering an elastic-plastic material , hence the elastic-plastic option has been included .

The relationship between stress and strain in the elastic range is given by Hooke's laws,whiich can be expressed as

$$[\sigma]=[D^e][\varepsilon]$$

where $[\sigma]=\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\end{bmatrix}$ $[\varepsilon]=\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\end{bmatrix}$ (17)

and $[D^e] = [E/(1+\upsilon)] \begin{bmatrix} (1-\upsilon)/(1-2\upsilon) & (\upsilon)/(1-2\upsilon) & (\upsilon)/(1-2\upsilon) \\ (\upsilon)/(1-2\upsilon) & (1-\upsilon)/(1-2\upsilon) & (\upsilon)/(1-2\upsilon) \\ (\upsilon)/(1-2\upsilon) & (\upsilon)/(1-2\upsilon) & (1-\upsilon)/(1-2\upsilon) \end{bmatrix}$

where υ=Poisson's ratio

and E=Young's modulus

For the case of plane stress $[\sigma]$, $[\varepsilon]$ and $[D^e]$ become

$$[\sigma] = \begin{bmatrix} \sigma_x \\ \sigma_y \end{bmatrix} \qquad [\varepsilon] = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \end{bmatrix} \qquad [D^e] = [E / (1-\upsilon^2)] \begin{bmatrix} 1 & (\upsilon) \\ (\upsilon) & 1 \end{bmatrix}$$

There are various statements of the plastic yield criteria, the von Mises yield criteria states : yielding occurs in a stress system when the maximum shear strain energy is equal to the shear strain energy at yield in uniaxial tension.

or,

$$[(\sigma_x-\sigma_y)^2+ (\sigma_y-\sigma_z)^2+ (\sigma_z-\sigma_x)^2]\geq 2Y^2 \qquad (18)$$

where Y is the material yield stress

$\sigma_x,\sigma_y,\sigma_z$ are the principal stresses

The plastic stress-strain relationship used in the elastic - plastic option is the one derived by Yamada[49], by inverting the Prandtl-Reuss relationships, and can be expressed as:

$$[\delta\sigma]= [D^p][\delta\varepsilon]$$

where $[\delta\sigma]= \begin{bmatrix}\delta\sigma_x \\ \delta\sigma_y \\ \delta\sigma_z\end{bmatrix}$ $[\delta\varepsilon]= \begin{bmatrix}\delta\varepsilon_x \\ \delta\varepsilon_y \\ \delta\varepsilon_z\end{bmatrix}$

(19)

and

$$[D^P]=[E/(1+\upsilon)]\begin{bmatrix}(1-\upsilon)/(1-2\upsilon)]-(\sigma_x')^2/S & & \text{SYMMETRICAL} \\ (\upsilon)/(1-2\upsilon)]-(\sigma_x'\sigma_y')/S & [(1-\upsilon)/(1-2\upsilon)]-(\sigma_y')^2/S & \\ (\upsilon)/(1-2\upsilon)]-(\sigma_x'\sigma_z')/S & [(\upsilon)/(1-2\upsilon)]-(\sigma_z'\sigma_y')/S & [(1-\upsilon)/(1-2\upsilon)]-(\sigma_z')^2/S\end{bmatrix}$$

where

υ is Poisson's ratio

σ_x' is $(2\sigma_x-\sigma_y-\sigma_z)/3$

σ_y' is $(2\sigma_y-\sigma_x-\sigma_z)/3$

σ_z' is $(2\sigma_z-\sigma_y-\sigma_x)/3$

S is $(2/3)\bar{\sigma}^2[1+H'/(3G)]$

G is $E/[2(1+\upsilon)]$

$\bar{\sigma}$ is $(1/\sqrt{2})[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2]^{1/2}$

H' $=\delta\bar{\sigma}/\delta\bar{\varepsilon}$, which is the material strain hardening rate and corresponds to the slope of the equivalent stress-strain curve.

For the case of plane stress $[\sigma]$, [e] and $[D^P]$ become

$$[\sigma] = \begin{bmatrix}\sigma_x \\ \sigma_y\end{bmatrix} \quad [\varepsilon] = \begin{bmatrix}\varepsilon_x \\ \varepsilon_y\end{bmatrix} \quad [D^P] = [E/Q] \begin{bmatrix}(\sigma_y')^2 + 2P & -\sigma_x'\sigma_y' + 2\upsilon P \\ -\sigma_x'\sigma_y' + 2\upsilon P & (\sigma_x')^2 + 2P\end{bmatrix}$$

where :

$P = (2H'/9E)\,\bar{\sigma}^2$

$Q = R + 2(1-\upsilon^2)P$

$R = (\sigma_x')^2 + 2\upsilon\sigma_x'\sigma_y' + (\sigma_y')^2$

7.7. CALCULATING INTERNAL POWER OF DEFORMATION

The previous sections have detailed the means of calculating the strain field and the corresponding stress field for the metal between two passes of the cold roll forming process. This section will be concerned with calculating the internal power of deformation,where this is given by [56]

$$W=\int \bar{\sigma}\dot{\varepsilon}dV \qquad (20)$$

where

W is the power of deformation

σ is the equivalent stress

$\dot{\varepsilon}$ is the equivalent strain rate

dV is the elemental volume

and

$$\bar{\sigma}=(1/\sqrt{2})[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2]^{1/2} \qquad (21)$$

$$\dot{\varepsilon}=[(\sqrt{2})/3][(\dot{\varepsilon}_x-\dot{\varepsilon}_y)^2+(\dot{\varepsilon}_y-\dot{\varepsilon}_z)^2+(\dot{\varepsilon}_z-\dot{\varepsilon}_x)^2]^{1/2} \qquad (22)$$

The derivation of equivalent stress and equivalent strain can be found in many metal forming textbooks, (for instance Johnson and Mellor[57]). For plane stress the equivalent stress and equivalent strain rate become :

$$\bar{\sigma}=\sqrt{\sigma_x^2-\sigma_x\sigma_y+\sigma_y^2} \qquad (21A)$$

$$\dot{\varepsilon}=(2/\sqrt{3})(\dot{\varepsilon}_x^2+\dot{\varepsilon}_x\dot{\varepsilon}_y+\dot{\varepsilon}_y^2)^{1/2} \qquad (22A)$$

Clearly the algorithms for calculating the strain field and the stress field are quite lengthy,therefore there is no definite statement for the stress or strain rate at a point and thus it is impossible to directly obtain a statement of the power. To overcome this,the power is calculated by dividing the strip into a suitable number of "brick elements" in the x,y,and z directions (Figure 7.20) and numerically integrated.

Equation (20) then becomes

$$W = \sum_{\substack{I=1,NELM \\ J=1,IX \\ K=1,IY \\ L=1,IZ}} \bar{\sigma}\dot{\varepsilon}dV \qquad (23)$$

where:

NELM is the number of elements

dV is the volume of a brick element

IX, IY, IZ are the number of brick elements in the transverse, longitudinal and thickness directions respectively

Each brick element can be uniquely identified by particular values of I,J,K,L. Thus the strain increment at a particular 'brick' element ($d\varepsilon$) can be calculated

$$d\varepsilon = \varepsilon_{(I,J,K,L)} - \varepsilon_{(I,J,K-1,L)}$$

$$d\varepsilon_X = \varepsilon_{X\,(I,J,K,L)} - \varepsilon_{X\,(I,J,K-1,L)}$$

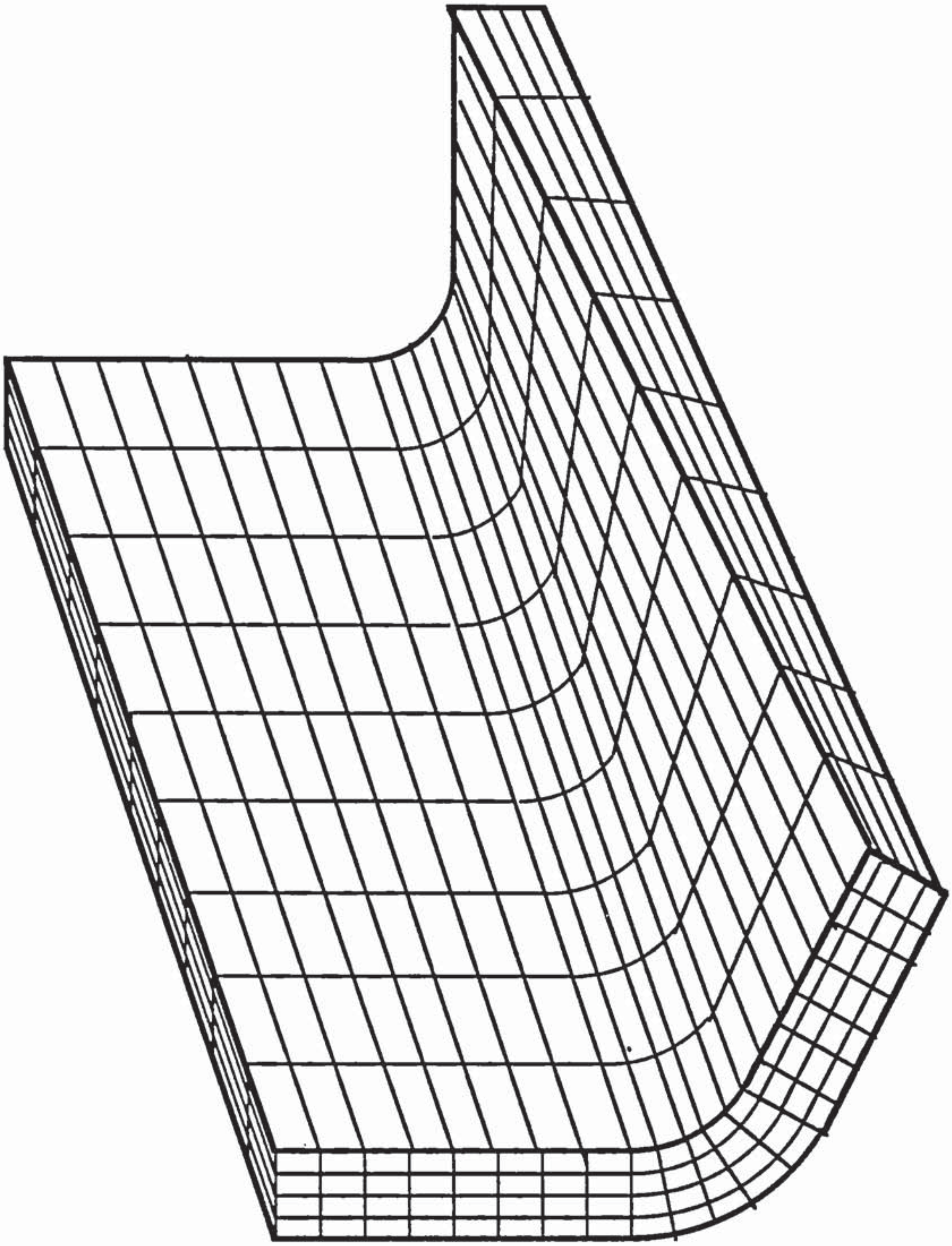


FIGURE 7.20 AN EXAMPLE OF HOW THE STRIP IS DIVIDED INTO "BRICK" ELEMENTS

$d\varepsilon_Y = \varepsilon_{Y(I,J,K,L)} - \varepsilon_{Y(I,J,K-1,L)}$

$d\varepsilon_Z = \varepsilon_{Z\,(I,J,K,L)} - \varepsilon_{Z\,(I,J,K-1,L)}$

Therefore the strain rate ($\dot{\varepsilon}$) can be calculated

$$\dot{\varepsilon} = (d\varepsilon\,/dy)(dy/dt)$$

where dy/dt is the velocity of rolling

dV the volume of the 'brick' element can be obtained from below

$$dV=(R_L.E.t)/(IX.IY.IZ) \qquad (24)$$

where:

R_L is the pass length

E is the element length

t is the thickness

7.8 MINIMISATION OF POWER

This section is concerned with the algorithm by which the power is minimised. To recap, the object is to find the shape of metal between passes (defined by the finished section file, the flower pattern file and the shape factor) which minimises the power term in equation (15). If equation (5) is used, for each 'active' bend at each stage there are two variables (a and b), hence at each stage the power is minimised by varying parameters equal to twice the number of active bends.

The choice of routine is complicated by the many algorithms available for the optimisation or minimisation of a function. However many of these methods, those which require the calculation of the first derivatives, can be eliminated. Additionally the method chosen had to be unconstrained but one which allowed unfeasible values to be discarded by the addition of a large penalty function.

The Nelder and Mead simplex method[58] (NMS) was eventually chosen. Comparisons between unconstrained minimisation techniques (Himmelblau[59] and Parkinson[60]) have shown that, whilst relatively slow, this method is robust in operation. The NMS method is iterative; where there are N independent values, the method proceeds by constructing a 'simplex' of N + 1 points in the N dimensional space of the variables. (To be most effective the problem should be scaled such that the variables are of order unity at the minima). The function values at each vertex are calculated. The vertex of the simplex with the largest function value is reflected in the centre of gravity of the remaining vertices and the function value at this new point is calculated and compared with the remaining function values. Depending on the outcome of this comparison the new point is accepted or rejected, a further expansion move may be made or a contraction carried out. When no further progress can be made the sides of the simplex are reduced in length and the method repeated until the minimum value is located.

The following section describes when a solution can be considered feasible . If a solution is unfeasible the value for power is made very large, this means in practice that it is not entered into the simplex and thus only feasible minimum values are found.

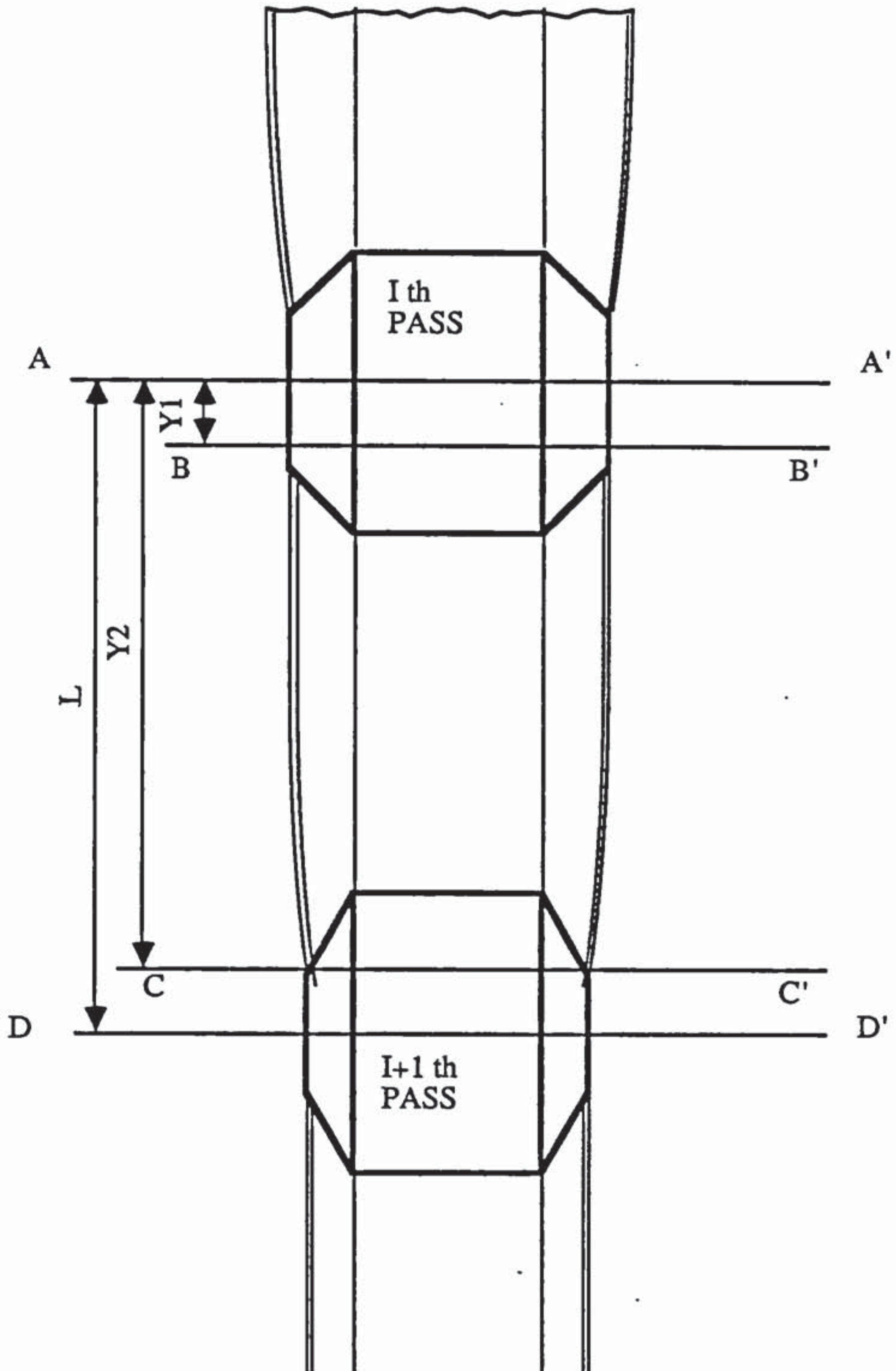


FIGURE 7.21 PLAN VIEW OF TWO PASSES IN THE ROLLING OF A CHANNEL SECTION

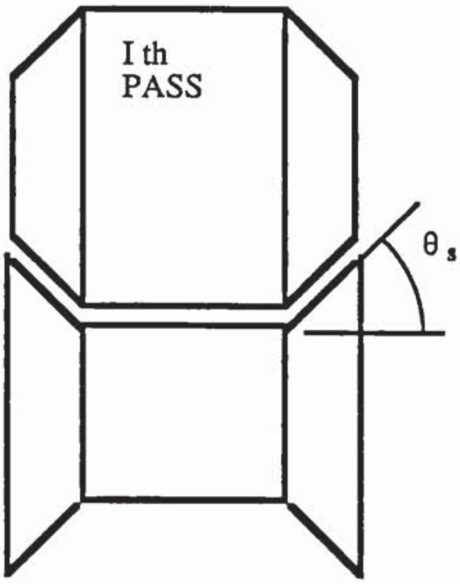


FIGURE 7.22A
SECTION THROUGH THE
ROLLS AT AA' (WITH
RESPECT TO FIG 7.21)

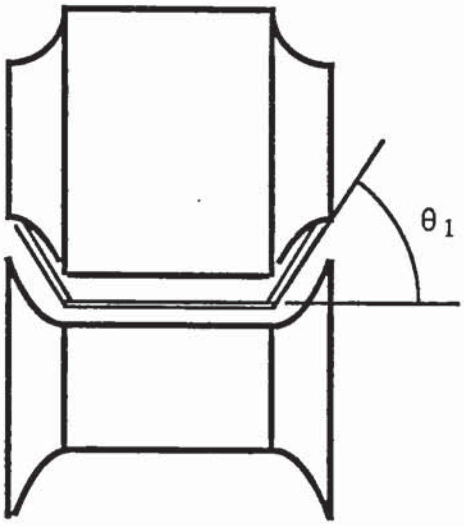


FIGURE 7.22B
SECTION THROUGH THE
ROLLS AT BB' (WITH
RESPECT TO FIG 7.21)

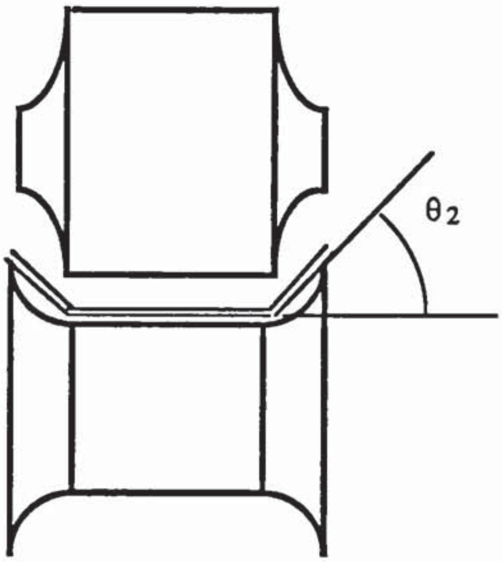


FIGURE 7.22C
SECTION THROUGH THE
ROLLS AT CC' (WITH
RESPECT TO FIG 7.21)

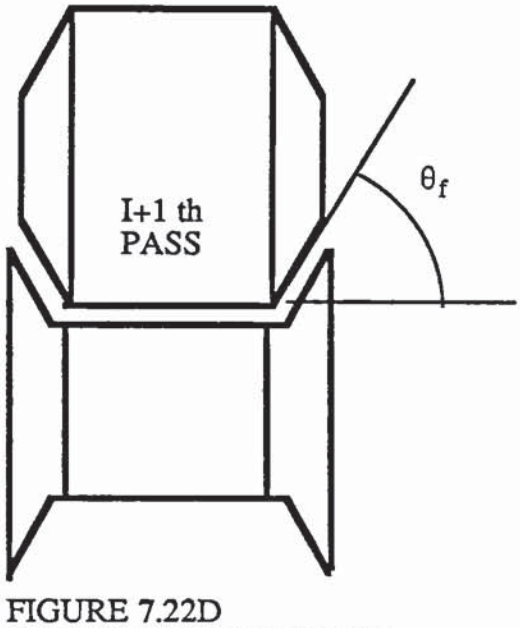


FIGURE 7.22D
SECTION THROUGH THE
ROLLS AT DD' (WITH
RESPECT TO FIG 7.21)

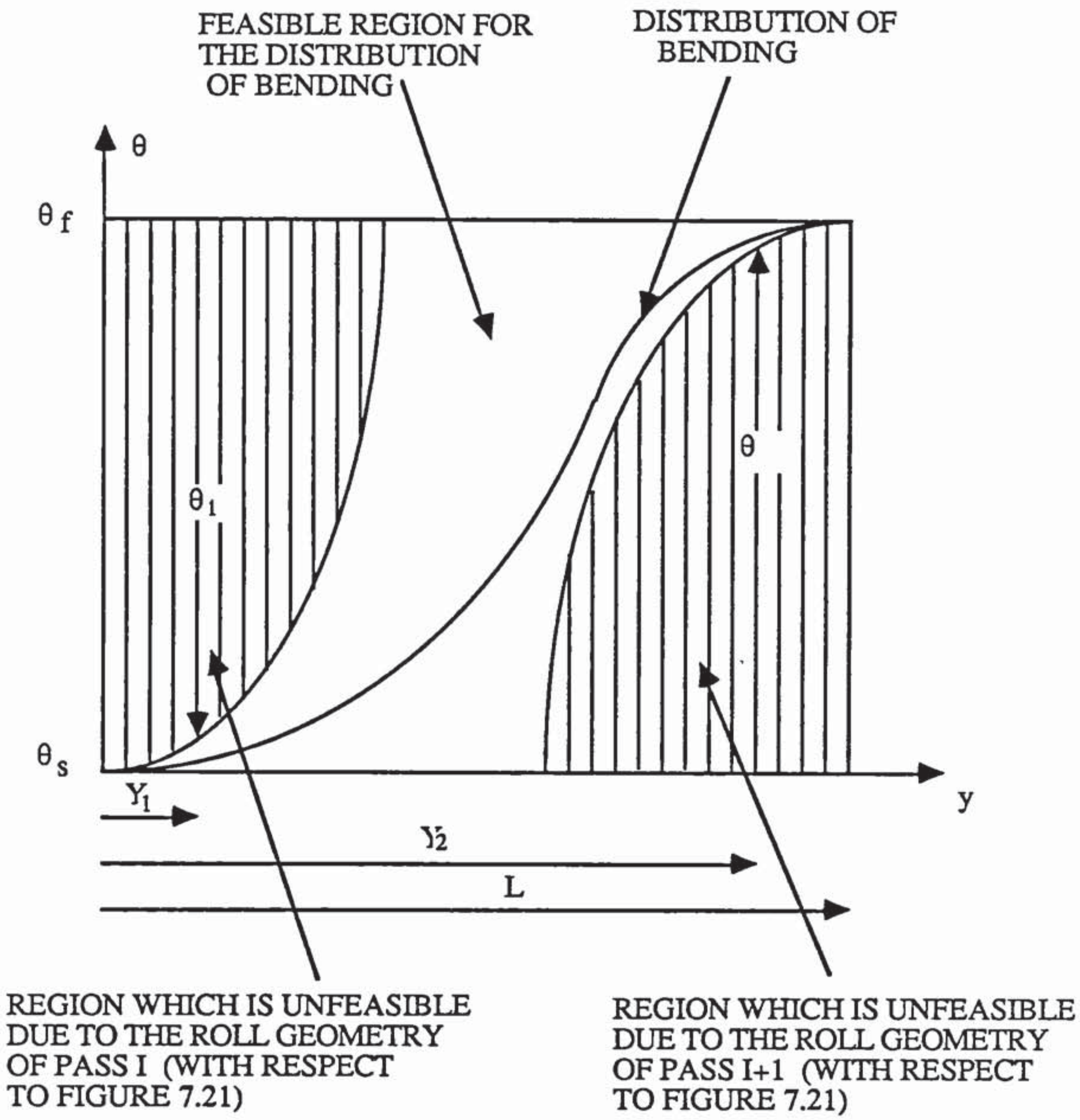


FIGURE 7.23 FEASIBLE REGION FOR THE DISTRIBUTION OF BENDING

7.8.1 FEASIBLE MINIMUM VALUES

The previous section described the means by which a minimum value is reached. However of the possible range of metal shapes suggested by the shape factor not all can be considered feasible. Considering Figure 7.21 ,which is a plan view of the two stages in the rolling of a channel; Figure 7.22A, which shows a cross section through the rolls at y=0 ;Figure 7.22B, which shows a cross section through the rolls at $y=y_1$; Figure 7.22C ,which shows a cross section through the rolls at $y=y_2$ and Figure 7.22D which shows a cross section through the rolls at y=L ,where L is the pass length.

At y=0 the channel profile is dictated by the roll shape and the angle of bending must equal θ_s. At BB' a distance y_1 from the first roll, the profile is restricted by the rolls and the angle of bending must be be less than θ_1. At $y=y_2$ the profile is again restricted by the rolls and the angle of bending must be greater than θ_2. At y=L the channel profile is dictated by the roll shape and the angle of bending must equal θ_f.

Thus, if the distribution of bending angle through the pass is plotted it would be restricted to a feasible region, by the three dimensional solid of the rolls, in the manner shown in Figure 7.23.

For the case of the channel the constraints on the distribution of bending can be derived by geometry, however for the general case the constraints are more complex. Thus a numerical method of testing whether a shape proposed by the minimisation routine is feasible, or unfeasible, has been developed and is described below. Considering Figure 7.24, the general equation of a linear element on the roll surface is given by the following equation

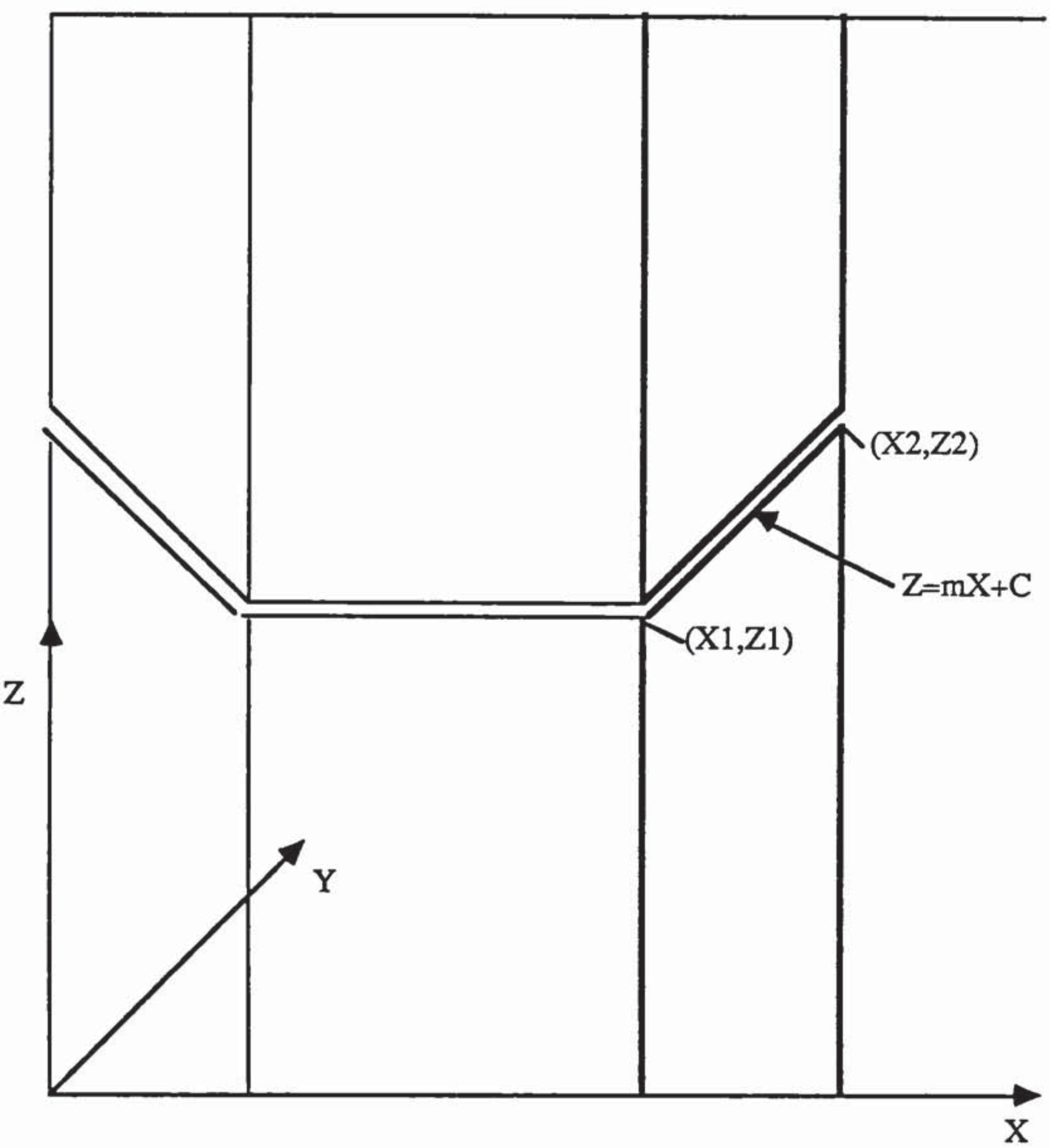


FIG 7.24 GEOMETRIC DEFINITION OF ROLL SURFACE

$$z = mx+c \qquad x_1 < x < x_2$$

The equation of the cone caused rotating the line about z=0 is given by

$$z^2=(mx+c)^2-y^2 \qquad x_1<x<x_2 \qquad (25)$$

At any distance y from the first roll the equation of a linear element of the sheet metal is given by :

$$z=m_1 x+c_1 \qquad (26)$$

Where $m_1 = \tan(\theta)$ and θ is given by the shape factor.

Combining (25) and (26)

$$(m_1 x+c_1)^2=(mx+c)^2-y^2$$

$$x^2(m^2-m_1^2)+x(2cm-2c_1m_1)+c^2-y^2-c_1^2=0 \qquad (27)$$

Thus the metal will collide with the roll if the solution to (27) is greater than x_1 and less than x_2. As was previously mentioned the method of testing whether a proposed shape is feasible is numeric. The logic of the method is shown in Figure 7.25. Essentially, for each linear element on the section the values m and c are calculated, and for five values of y the values m_1 and c_1 are calculated. For each value of y the solutions of equation (27) are found and the feasibility of the shape assessed.

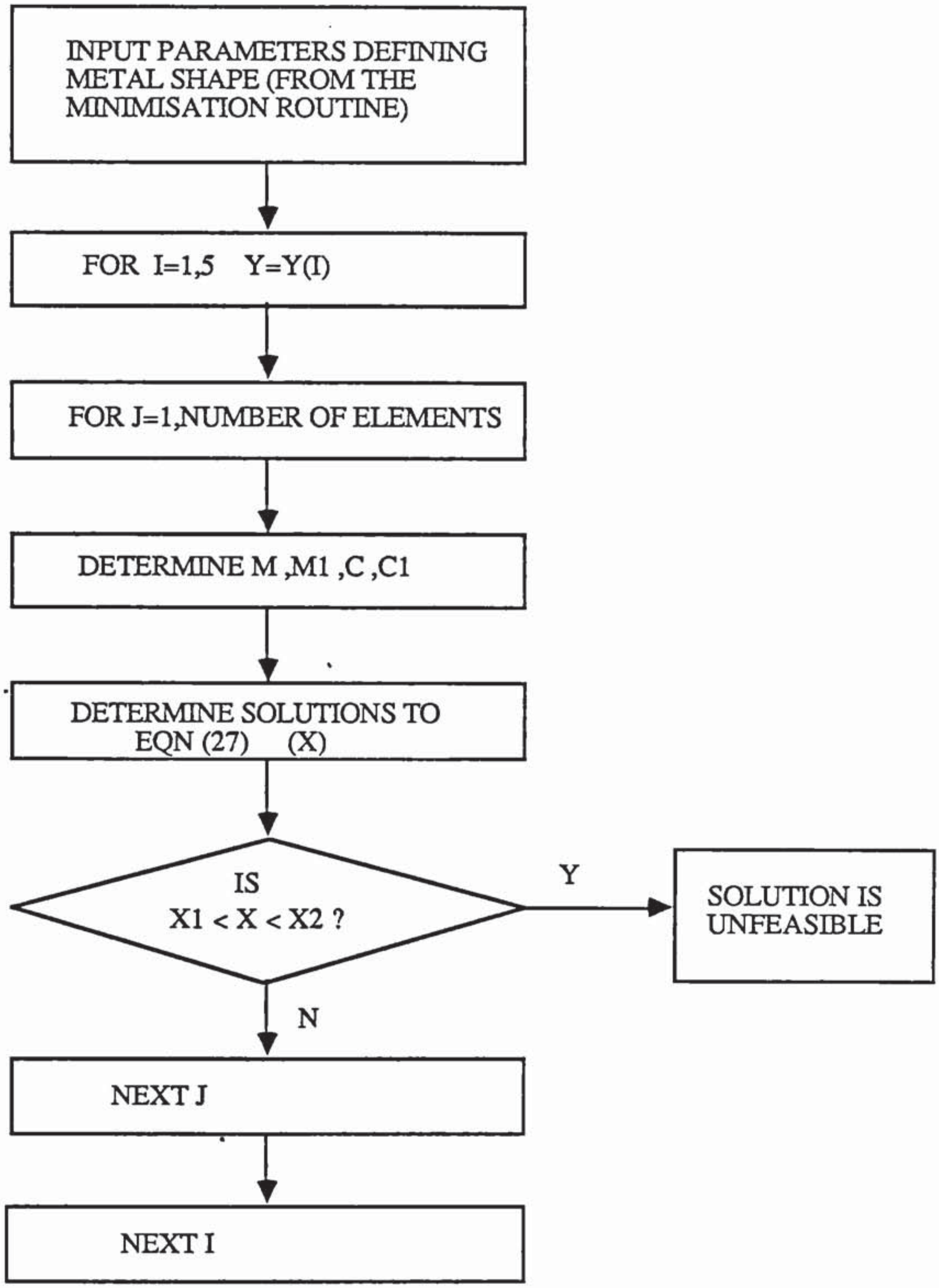


FIGURE 7.25 LOGIC OF THE ROUTINE FOR THE CONSTRAINING OF THE MINIMISATION ROUTINE

7.9 SOFTWARE IMPLEMENTATION

The previous sections in the chapter have described the individual modules of the model. This section will describe the practical implementation of the model as a computer program. The various levels of routines in the model are detailed in Figure 7.26 where the individual routine functions are described briefly in table 7.1. The minimisation function (routine EO4CCF) was taken from the National Algorithm Group library and requires the provision of a routine (FUNCT) which provides the value of the function (in this case power) which is being minimised.

As was mentioned earlier, the software has been constructed such that individual elements of the model logic can be isolated and modified. For instance, the shape factor is contained in one routine , allowing alternative shape factors to be easily assessed.

7.10 DATA OUTPUT

The output created when the numerical analysis of the form roll design is performed consists of three parts.

(1) The NX-file. The NX-file contains the parameters a and b from equation (6), which define the metal shape. The data is in groups of five values.

ELNO - The element number

STGNO - The stage number

SIDE - 1 = left hand side 2 = right hand side

A - The variable a for the bend defined by ELNO, STGNO and SIDE

B - The variable b for the bend defined by ELNO, STGNO and SIDE

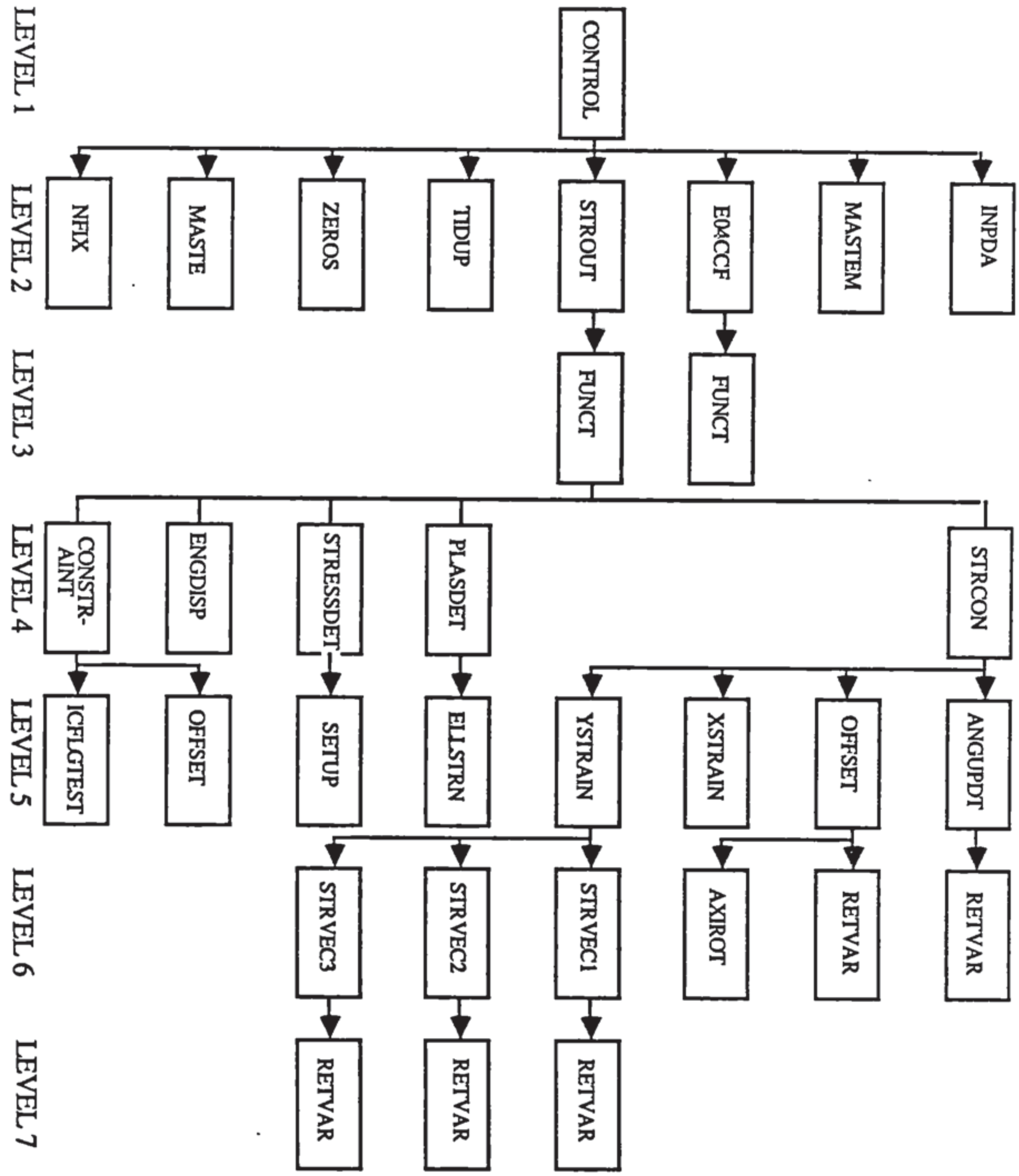


FIGURE 7.26 HIERARCHY OF SUBROUTINES IN THE NUMERICAL ANALYSIS SOFTWARE

(2) The NR / NS - FILE. The NR-file contains the longitudinal strain distribution for the right hand side of one pass at one stage. The NS-file contains the longitudinal strain distribution for the left hand side of one pass at one stage. When the NR- or NS- files are created the values IX, IY, IZ defining the number of brick elements in each element are set to 6,20,6 as a standard for exchange with the graphical output routines described in the following chapter.

(3) The log file. The log file contains information which describes the running of the program, the system messages generated by the computer and the results of the analysis.

TABLE 7.1

	Level	Description
CONTROL	1	Overall control module
INPDA	2	Inputs material, geometric and process data
EO4CCF	2	Minimisation routine
STROUT	2	Outputs model results
TIDUP	2	Transfers final values of previous pass into initial values of subsequent pass
ZEROS	2	Returns values of arrays to zero between passes
MASTEM	2	Transfers right side of section into model
MASTE	2	Transfers left side of section into model
NFIX	2	Allows the user to rerun model with known variable data
FUNCT	3	Provides power value for specific variable data provided by minimisation routine
STRCON	4	Derives strain field by method detailed in section 7.5
PLASDET	4	Determines whether an element has plastically yielded.
STRESSDET	4	Calculates stress values for plastically yielded element.
ENGDISP	4	Calculates power
CONSTRAINT	4	Determines whether variable is feasible
ANGUPDT	5	Sets up arrays defining the angle of inclination at certain points thoughout the pass
OFFSET	5	Calculates the 'offset' values of each element
YSTRAIN	5	Calculates the longitudinal straining
XSTRAIN	5	Calculate the transverse and radial straining
ELLSTRN	5	Calculates stress values for elastic elements

SETUP	5	Sets up the plastic stress strain matrix
IFLAGTEST	5	Determines whether the template shape proposed by the minimum values and the roll shape collide
RETVAR	6	Calculates the shape factor
AXIROT	6	A utility routine for rotating axes and calculating new axial increments
STRVEC1	7	Contains eqn (6)
STRVEC2	7	Contains eqn (7)

CHAPTER 8

COMPUTER AIDED FLOWER PATTERN DESIGN

8.1 INTRODUCTION

As was emphasised in chapter 3 the flower pattern is central to the process of form roll design. However, considering the flower patterns importance, there are few aids to the designer in either assessing flower pattern design or helping the designer generate a flower pattern design.

Since presently it is impossible to generate consistently effective flower pattern designs, two complementary approachs are described in this chapter. Firstly, techniques which attrempt analysis or which provide an enhanced visualisation of the effects of a design are described. Secondly, a program which incorporates existing knowledge about flower pattern design to partially generate a flower pattern design is described. The two approachs can be considered complementary since they are working from opposite directions to achieve the same objective, consistently effective flower pattern design.

Two methods, which illustrate the two approachs, have already been discussed. The automatic percentage composite element length option, described in section 4.4, aids the designer by generating the optimum bend radius. The computer aided springback analysis program ,described in section 6.6.1, assists the designer by allowing him to obtain a graphical representation of the general tendency of any bend to return to its original shape.

The previous chapter described a method of numerical analysis of form roll design. This chapter is to a larger extent concerned with methods for providing the designer with tools for enhancing his visualisation of the effects of flower pattern design. Pictorial representation is the favoured medium of virtually all designers, hence the computer aided design system's ability to rapidly generate images which reflect different possible designs is one of its greatest assets. In the design of form rolls the following pictorial representations have been developed:

(1) Plan view

(2) Side view

(3) Wire frame view

(4) Metal shape view

(5) Single pass metal shape view

Where the meaning of these terms will be explained in the following sections.

8.2 PLAN AND SIDE VIEW SOFTWARE

The purpose of the plan view software and the side view software is to improve the designer's visualisation of the effects of the flower pattern design by showing an idealised representation of the flow of metal as it passes along the mill. This is necessary because successful cold roll forming requires a smooth flow of metal through the mill and this is not easy to visualise by consulting the flower pattern alone.

Both the plan view (Figure 8.1) and the side view (Figure 8.2) draw smooth curves through the points defined by the position of each element boundary at each pass. The parallel lines in Figures 8.1 and 8.2, represent the positions of the centre line of each pass on the mill. The drawings are automatically scaled to fit the screen., the result of this scaling is to grossly compress the view along the length of the mill.

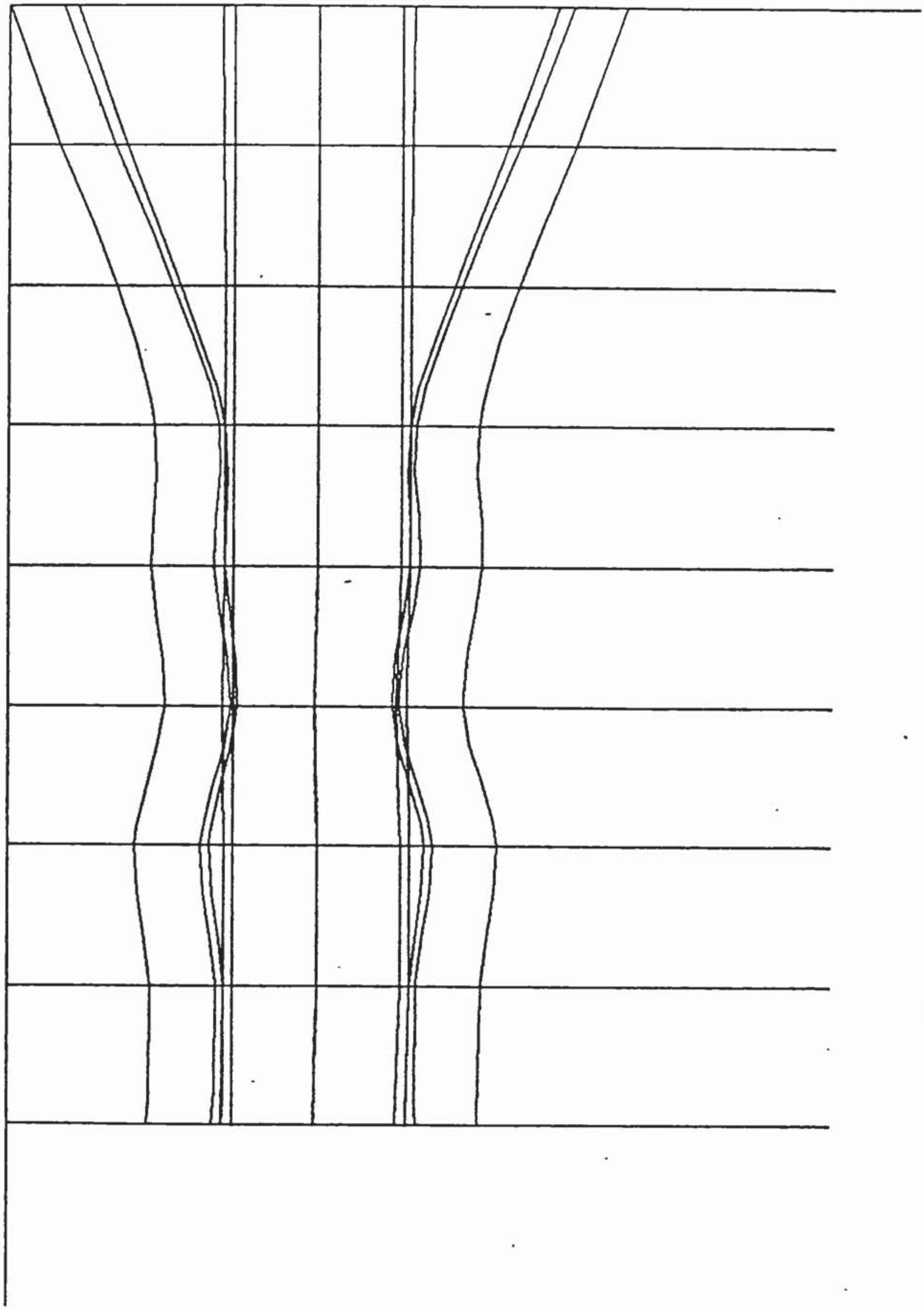


FIGURE 8.1 PLAN VIEW

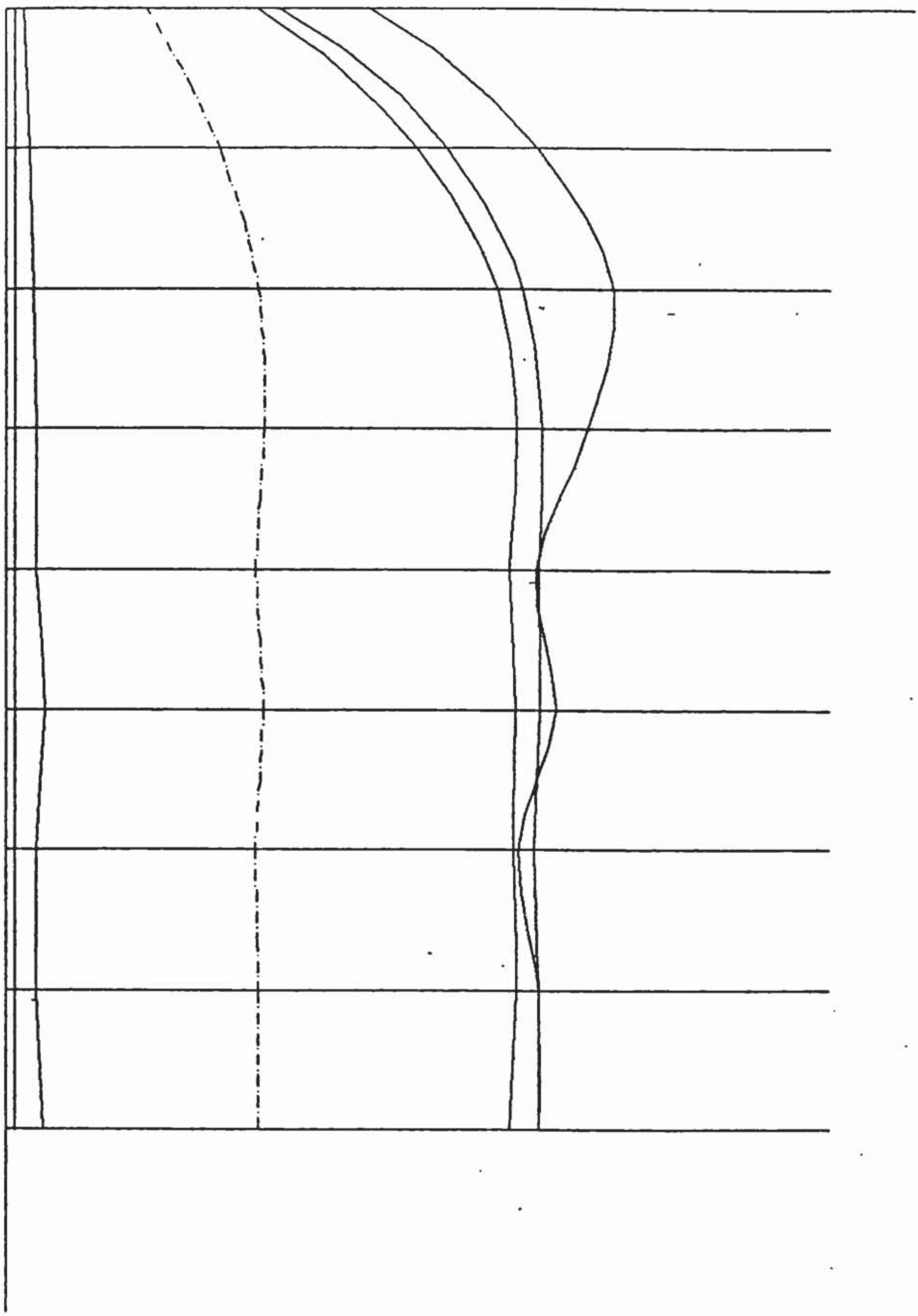


FIGURE 8.2 SIDE VIEW

The plan view shows an idealised view looking from above the mill. The program combines, the data file produced by the template program with information input via the keyboard (which defines the interpass distances) to produce the plan view. It is also possible to selectively display individual elements, when it is confusing to display all the curves simultaneously, thus clarifying the view.

The side view shows an idealised view of the flow of metal along the mill (looking from the right hand side when looking upstream). Again, it combines the data file produced by the template program with information input via the keyboard, (which defines each interpass distance and each pass height), to produce the drawing. It is also possible to selectively display individual elements, (where this can clarify the view).

On both the side view and the plan view the centroid movement is shown as a chained line. The representation of the centroid is important because many designers believe that keeping the centroid movement as small as possible improves the flower pattern design. Thus by consulting the plan view and side view it is possible for the designer to observe the effect of varying pass height and interpass distance on both the smoothness of flow and the centroid movement. Also ,using the plan and side views, it is possible to easily alter the flower pattern at the design stage and hence observe the effect of varying flower patterns on the metal flow. The views may also be used to improve the flow of old designs by specifying a different interpass distance.

8.3 WIRE FRAME VIEW SOFTWARE

The purpose of the wire frame software is to improve the designers three dimensional visualisation of the shape of metal as it moves along the mill. It was felt that there was a need for this software since, whilst the plan and side views improve the visualisation of metal flow, often it is only by considering the three dimensional view that one gets a full appreciation of the metals shape.

In general, wire frame is the name given to a view which attempts to represent a complex solid or surface shape by a series of lines. In cold roll forming an idealised view of the shape of the metal along the mill is given by plotting the template shapes and joining each element boundary by a straight line to the element boundary on the next stage.

The wire frame program takes the data file produced by the template program and combines it with information input via the keyboard (to define the interpass distance and the viewing angle) to produce the wire frame drawing (Figure 8.3). The program is self scaling so as to fit the available screen size and whilst this is obviously necessary it is also confusing in that it grossly distorts the shape. With small sections, in particular, there is a tendency for the forming to look more severe than is actually the case to. To overcome this the actual metal movement between passes is shown for both the left hand and right hand sides of the section. Since the scaling of the metal movement axes are never altered the designer gets an absolute indication of the scale of the section.

The angle of the section centre line relative to the horizontal (referred to as the viewing angle) can be altered so that the designer can effectively view the wire frame from a variety of positions. From practical observation it can be said, that the wire frame view has been much appreciated by designer and that flower pattern designs have improved as a result.

8.4 METAL SHAPE VIEW SOFTWARE

From the wire frame view the design is given an invaluable pseudo-three dimensional preview of the metal shape as it passes through the mill. However, the wire frame representation is unrealistic in that the metal movement between passes is portrayed as a straight line (Figure 8.4A) whereas in practice the deformation will tend to be more severe towards the end of the pass (Figure 8.4B). Therefore, particularly with short legs, the severity of forming will be seriously underestimated if the wire frame view alone is

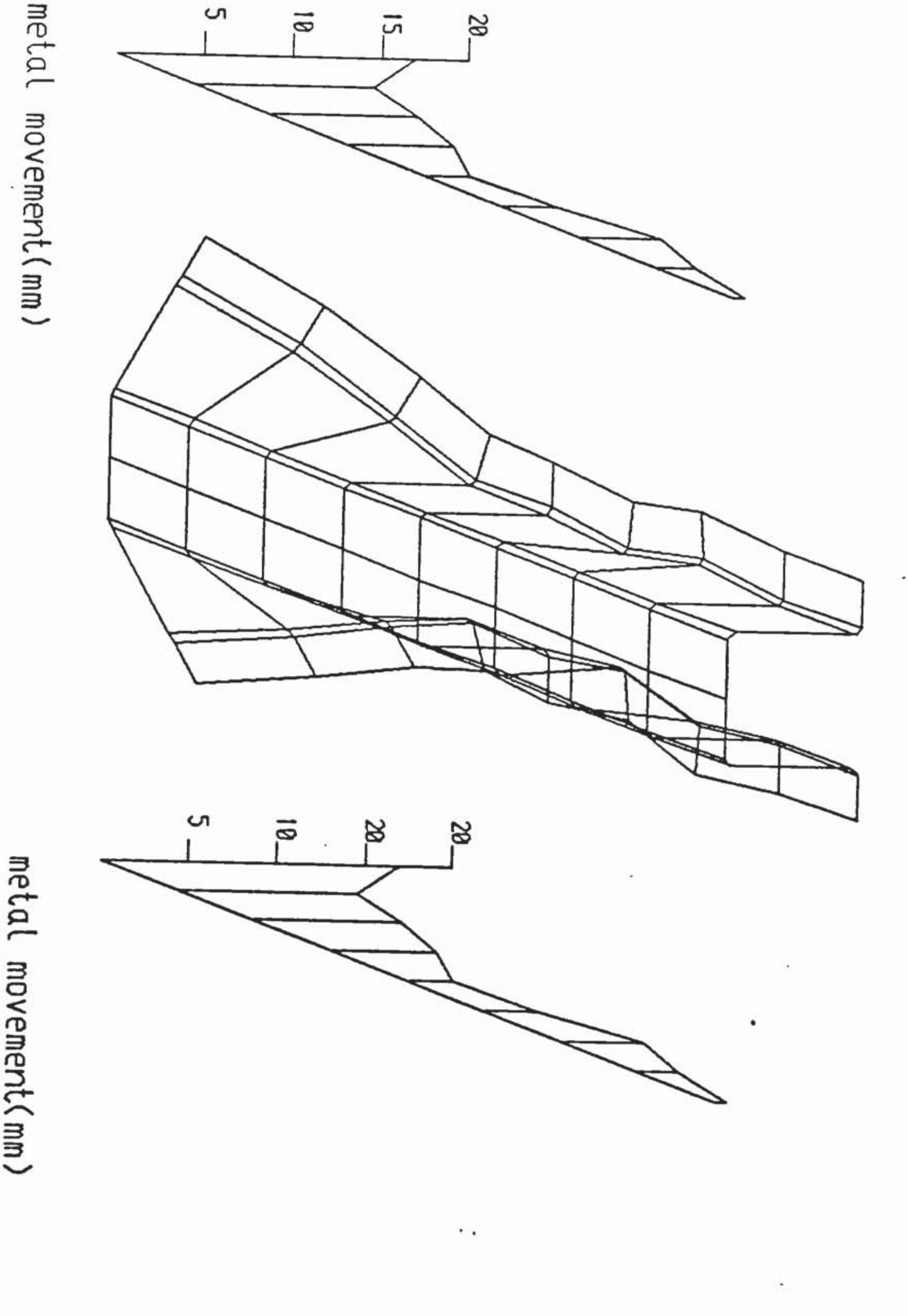


FIGURE 8.3 WIRE FRAME VIEW

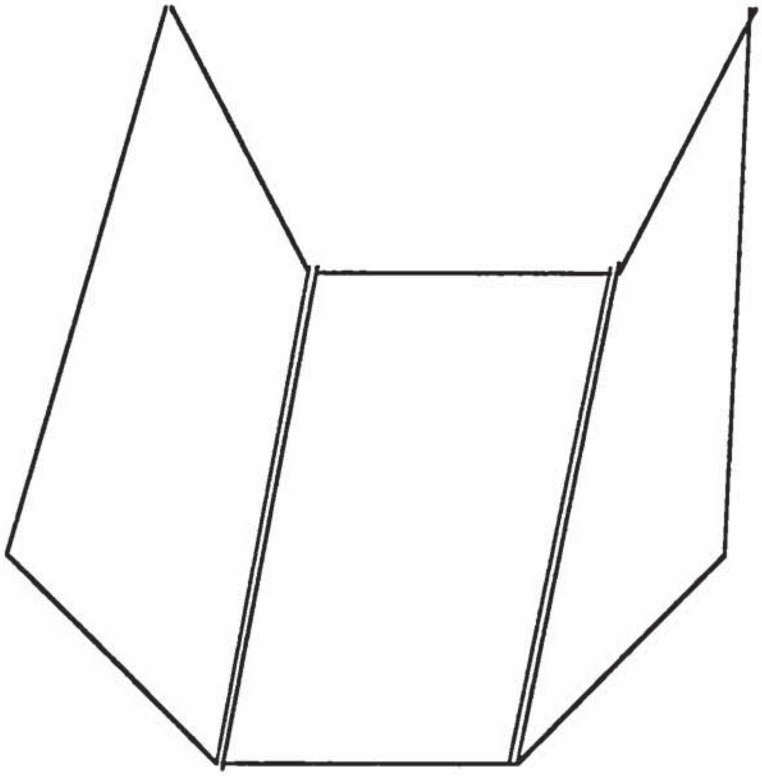


FIGURE 8.4A IDEALISED METAL MOVEMENT

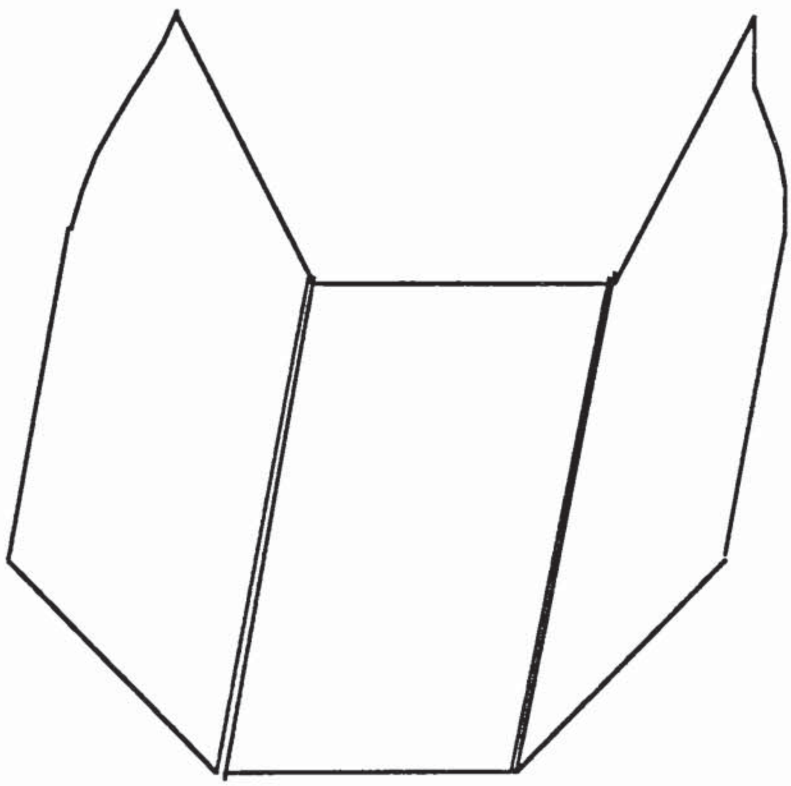


FIGURE 8.4B ACTUAL METAL MOVEMENT

considered. For this reason the metal shape view has been developed (Figure 8.5), this is intended as a representation of the actual metal shape as it passes along the mill. The input to the program comprises of :

(1) The finished section file (the D-file)

(2) The flower pattern file (the F-file)

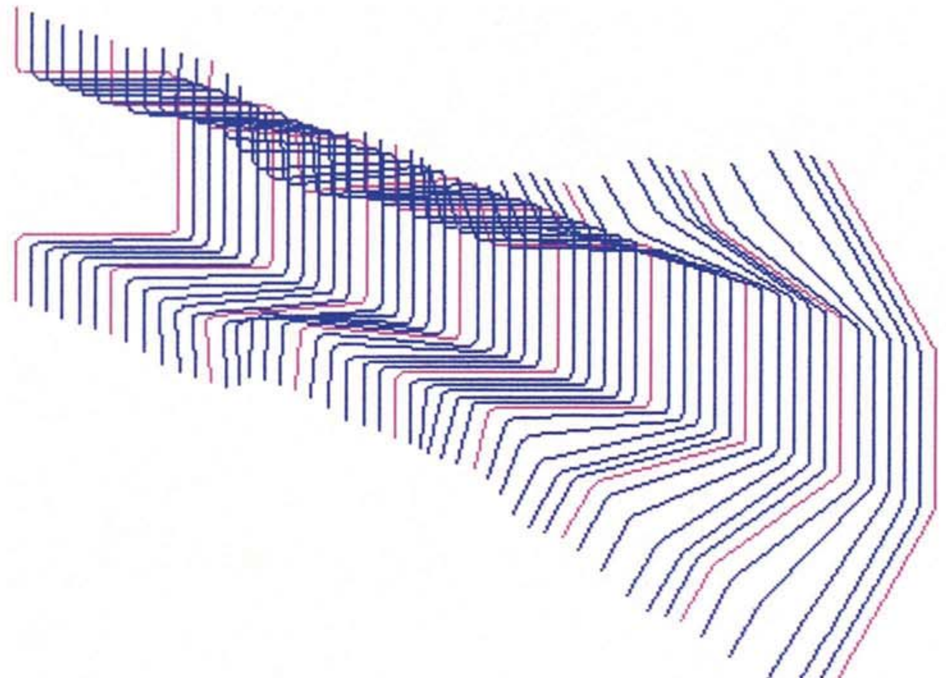
(3) An intermediate data file which contains information output from the model defining the metal shape. (The NX-file)

(4) Information input via the keyboard which defines the pass length and the viewing angle.

The program draws the template shapes for each pass, as in the wire frame view, then calculates new bend angles at a certain distance from each pass (by using one of the shape factors described in the previous chapter) and draws a further set of template shapes. This process is repeated until the total metal shape has been represented in this manner. The actual pass shape is represented in a different colour from the estimated metal shape. The program has been written so that the metal shape view is self scaling to fit the appropriate graphical device.

The metal shape view and the wire frame view can be said to be complementary, since, whilst the metal shape view program gives a more accurate representation, the wire frame view can be produced immediately the flower pattern has been input, wheras the metal shape view cannot be produced immediately, but requires the running of the model prior to its use.

Figure 8.5 Metal shape view



8.5 THE SINGLE PASS METAL SHAPE VIEW PROGRAM

As the title implies, the single pass metal shape view program isolates a single pass from the metal shape view (Figure 8.6). There are two main reasons why such a view should be of value. Firstly, the total metal shape may be an extremely complex three dimensional shape, therefore, particularly as the number of passes increase, it becomes difficult to visualise the deformation in specific regions from the total metal shape view. Secondly, the single pass view forms the ideal vehicle for outputting the results of numerical analysis. At present, the longitudinal straining is portrayed at each stage in this manner (Figure 8.7), since this is considered to be the most important parameter. However there is no reason why the view should not be used to output, say, stress or elastic energy. The input to the program comprises of:

(1) The finished section file (the D-file).

(2) The flower pattern file (the F-file).

(3) An intermediate data file which contains information output from the model and which defines the metal shape, (the NX-file).

(4) Information input via the keyboard which defines the viewing angle.

(5) If required, the data file containing the longitudinal strain data.

The program draws the template shape at the roll set commencing the pass and the roll set at the end of the pass. The program then calculates the new bend angles at a certain distance from each pass (by using one of the shape factors described in the previous chapter) and draws a further template. This process is repeated until a total of twenty one template shapes have been drawn. Having drawn the pass the longitudinal strains are superimposed onto the template framework ;where the medium of colour is used to represent different bands of strain (Figure 8.7).

Figure 8.6 Single Pass View

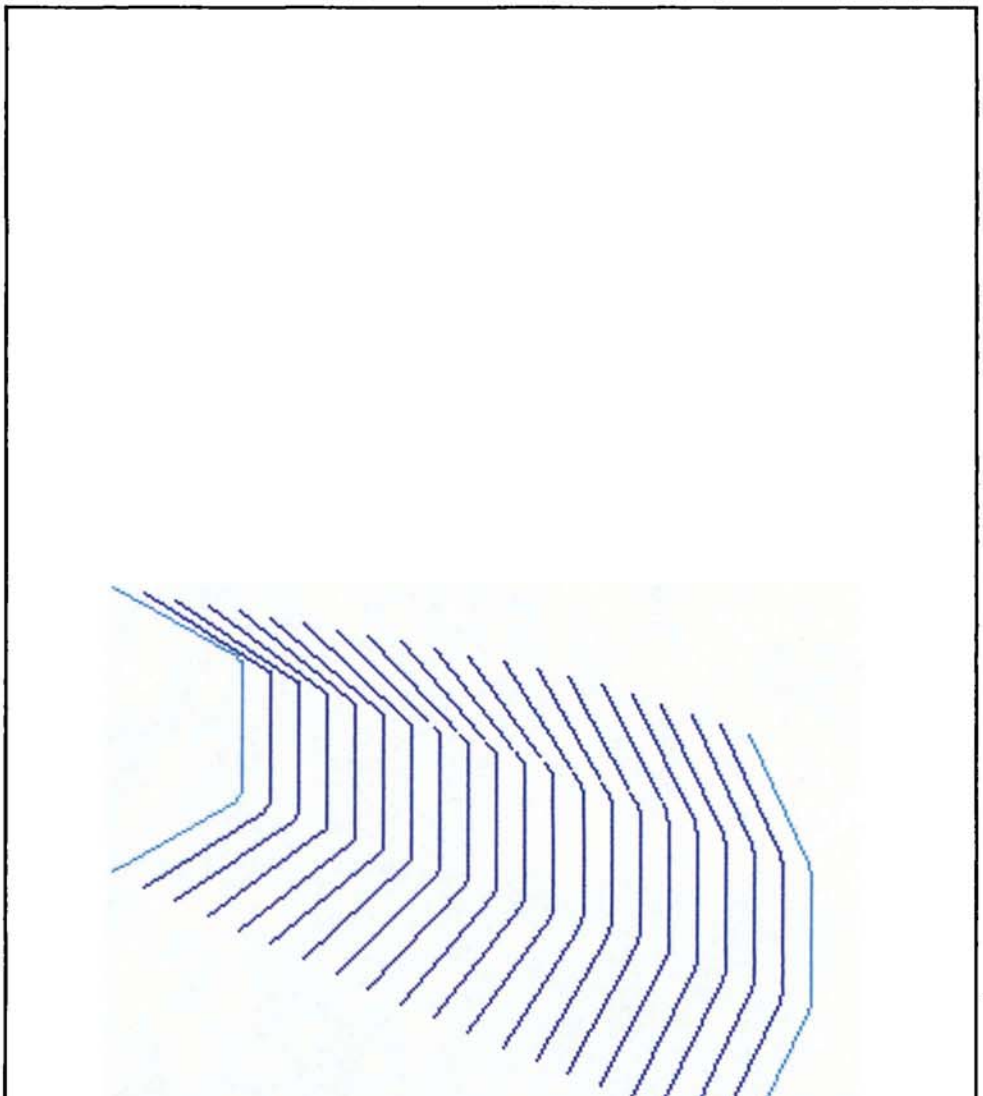
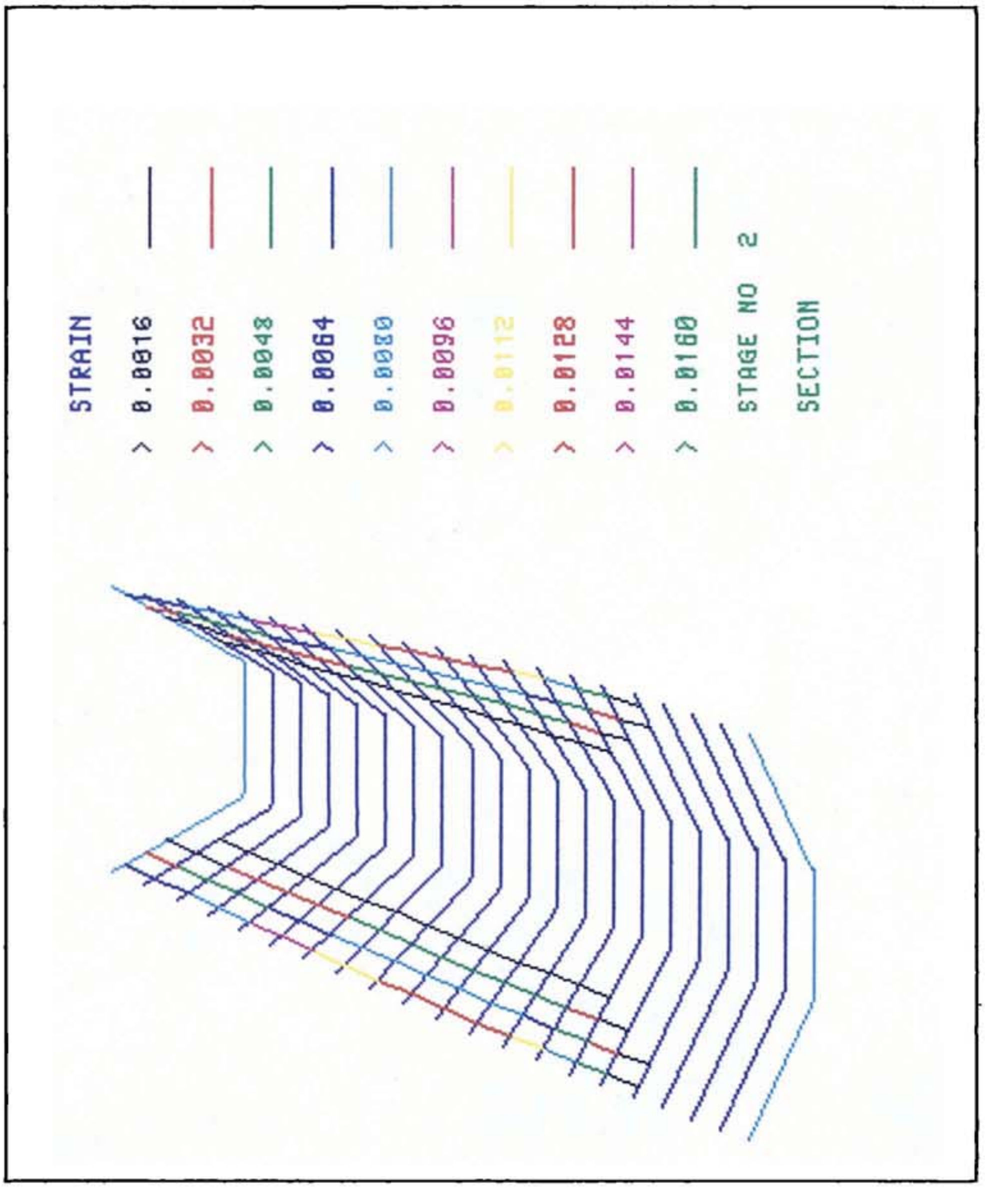


Figure 8.7 Longitudinal strain view



8.6 THE LIMITED INPUT FLOWER PATTERN SOFTWARE.

The flower pattern software was described previously , in section 4.4, and whilst this program has proved to be adequete in operation it was felt that it could be improved in three main areas.

Firstly , it was felt that the flower pattern program should more accurately reflect the manner in which the designer approachs the flower pattern design. As was mentioned previously , the design process can be considered in three main stages. Initially the designer decides on certain stages which he deems essential for the successful production of the section. Secondly , the designer decides how many passes should be used in moving from one 'compulsory pass' to the next and apportions the metal movement between passes. Finally the designer decides on the manner of forming bends.

Secondly it was felt that the stated system philosophy of combining maximum flexibilty with minimum input was not being achieved, in particular it was hoped that the second and third stages in the flower pattern design process could be automated. (Provided that suitable editing facilities were provided this could be achieved without loss of flexibilty).

Thirdly, it was felt that those methods which do exist to aid the designer, such as the forming angle theory and springback estimation should be incorporated into the program. Again where suitable editing facilities allow the designer ultimate flexibility.

Thus the limited input flower pattern program was developed and consisits of three sections, namely :

1 The first section inputs the compulsory passes and generates the intermediate passes with respect to user supplied information defining the constraints imposed by power

limitations and the maximum permissible metal movement.

2 The second section allows the designer to inspect the generated flower pattern, numerically and visually, and edit the generated flower pattern.

3 The third section controls the means of forming the bends by using the automatic percentage composite element length module.

The designer may enter the program at any of the three stages, providing that the preceding stages have been previously completed, thus allowing a design session to be interrupted and restarted. The software is highly interactive and a sample session is contained in appendix D.

8.6.1 FLOWER PATTERN GENERATION MODULE

The modules first task is to allow the designer to define the compulsory passes. This is performed in the same manner as the flower pattern definition program. When the final pass has been entered the partial flower pattern is displayed graphically on the screen, this gives the designer a visual interpretation of his input and hence reduces the possibility of error.

The second function of the program is to apply existing knowledge and designer defined constraints to generate the intermediate passes. The logic performed in generating these passes is detailed in Figure 8.8 and is best described step by step.

The first step is to monitor the strip edge to discern whether the strip edge moves through a "maximum position", (where the meaning of the term "maximum position" is explained below). With reference to Figure 8.9A, in moving from compulsory pass A to compulsory pass B the strip edge clearly has to pass through the point C.

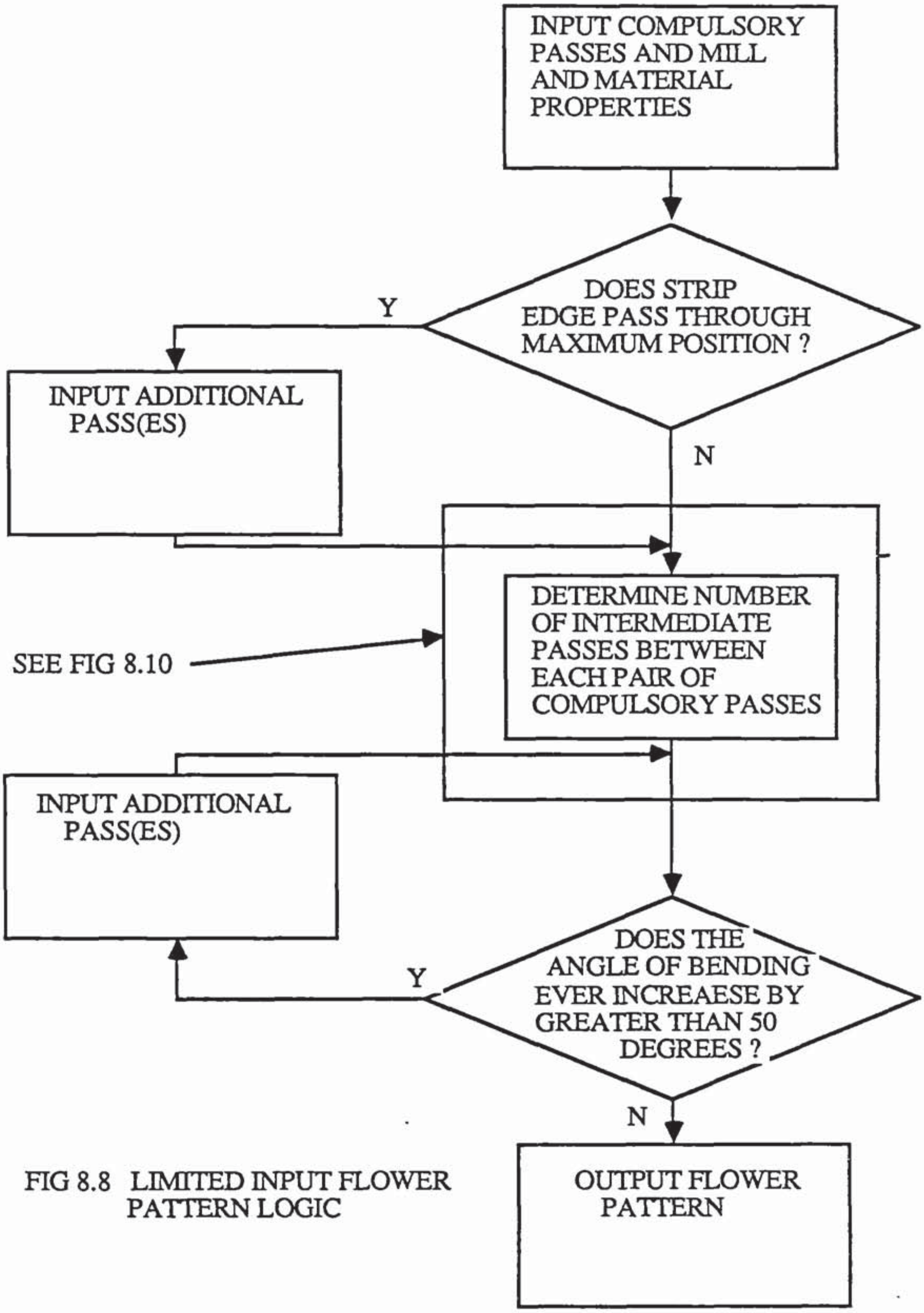


FIG 8.8 LIMITED INPUT FLOWER PATTERN LOGIC

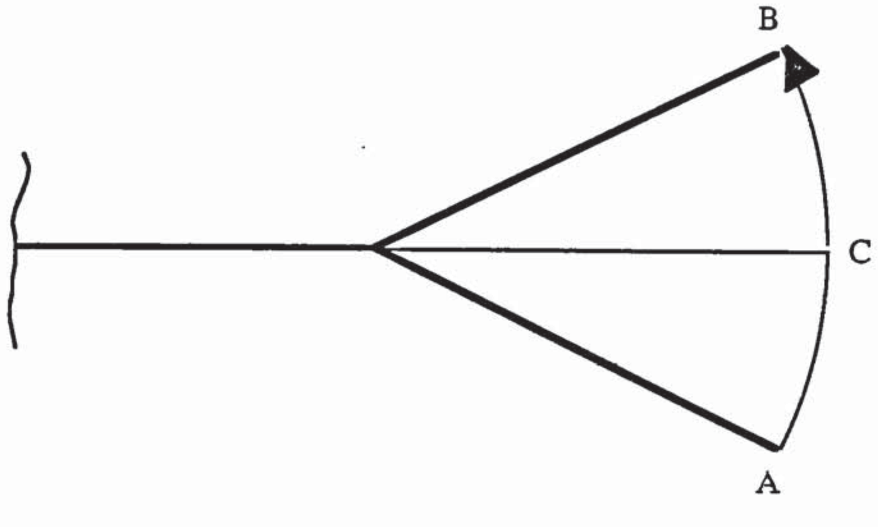


FIGURE 8.9A HORIZONTAL MAXIMUM POSITION

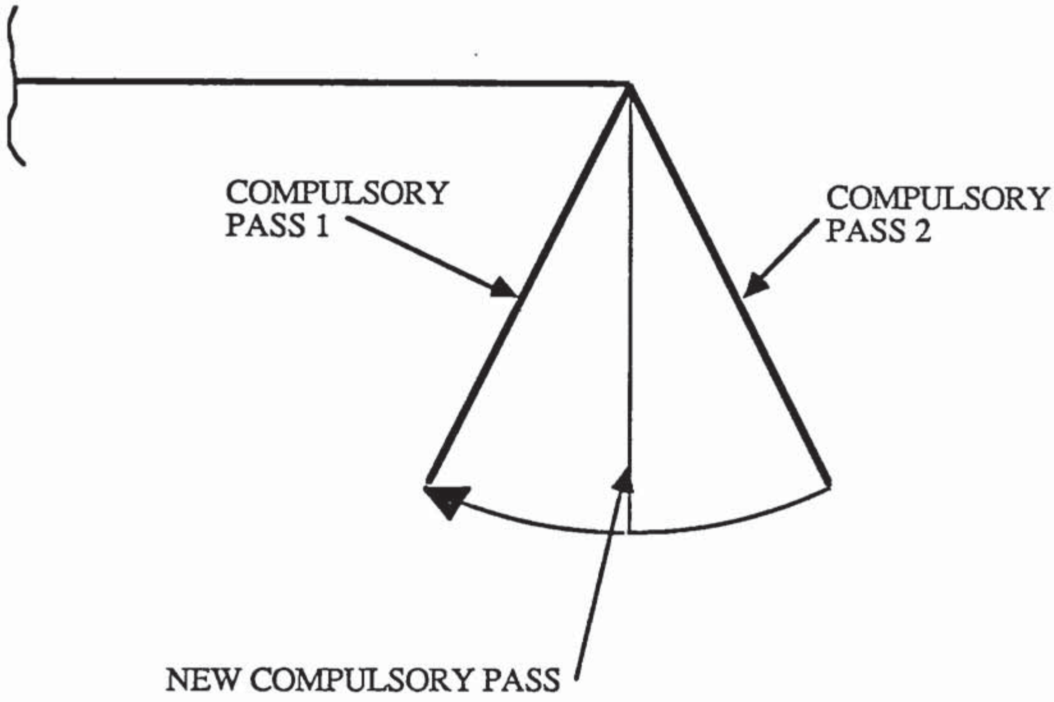


FIGURE 8.9B VERTICAL MAXIMUM POSITION

Thus, whilst the sideways movement between A and B appears to be small the actual metal movement is considerably larger. One of the commoner mistakes in flower pattern design occurs when this fact is disregarded. A good designer will always examine his flower pattern design for positions where the strip edge moves through the vertical or horizontal and, where necessary, include an additional pass at the maximum point. The program, then, tests for these maximum points in both the vertical and horizontal planes, where they occur an additional compulsory pass is included, as for example in Figure 8.9B.

Having, if necessary, modified the compulsory passes, the next stage is in determining the most efficient manner of generating the intermediate passes. Each pass must satisfy constraints limiting the maximum permissible metal movement and the maximum permissible power consumption. The most appropriate method of constraining metal movement is the forming angle theory, which was detailed in chapter 3, thus the designer is required to supply values defining the pass length and the maximum forming angle tolerable by the metal. The power consumption at each pass is limited to a value submitted by the designer which reflects the capacity of the rolling mill.

The number of passes necessary to move from one compulsory pass to the next, is calculated both to avoid exceeding the maximum permissible metal movement and the maximum available power, the required value is obviously the larger of these. Finally, it is necessary to consider springback when determining the number of intermediate passes required. It must be remembered that the shape of the metal defined by the flower pattern is only nominal and on leaving the rolls will be subject to springback. (Where the tendency to return to the original shape can be very large in certain cases). Thus, on entering the next pass the actual amount of deformation will be far greater than that indicated from merely considering the flower pattern. The neglect of this effect is one of the most common causes of inadequate flower pattern design, thus, it is important that the number of passes is modified to reflect the sections capacity to return to its original shape.

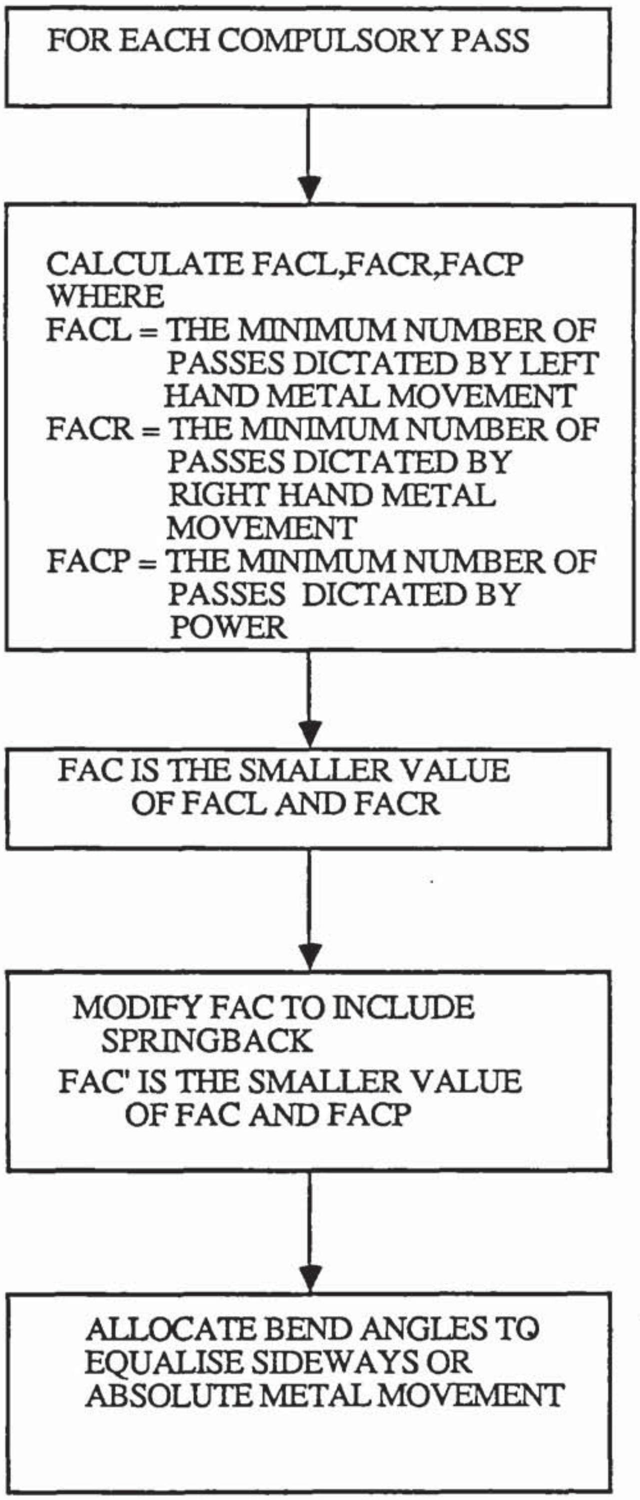


FIGURE 8.10 LOGIC FOR DETERMINING THE NUMBER OF INTERMEDIATE PASSES

The logic involved in the generation of intermediate passes is detailed diagrammatically by Figure 8.10, each stage in this logic will now be examined in more detail. A modified Angel's forming angle theory was adopted to monitor movement, this was since, the practical experience of the collaborative organisation was that by considering sideways metal movement a more effective flower pattern was developed. The sideway metal movement between successive compulsory passes (with reference to Figure 8.11) can be calculated by geometry.

where :

DX_r is the right hand sideways metal movement.

X_r is the right hand sideways distance from the section centre line.

X_r' is the right hand sideways distance from the section centre line at the preceding pass.

DX_l is the left hand sideways metal movement.

X_l is the left hand sideways distance from the section centre line .

X_l' is the left hand sideways distance from the section centre line at the preceding pass.

and

$$DX_l = | X_l - X_l' |$$

$$DX_r = | X_r - X_r' | \qquad (5)$$

in general X_r, X_r', X_l, X_l' can be obtained from the following expression

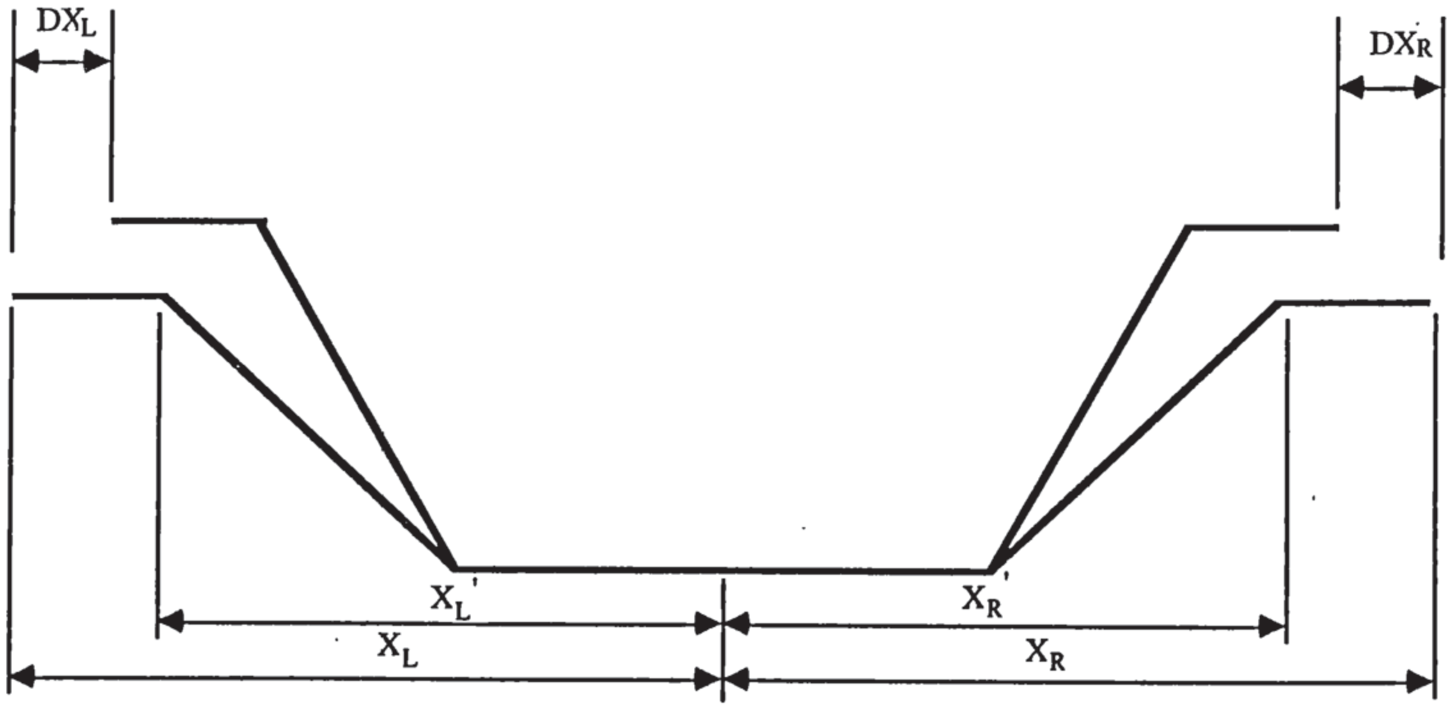


FIGURE 8.11 EXAMPLES OF SIDEWAYS METAL MOVRMENT

$$X = l_1 + 2((l_2/\theta_2)\sin(\theta_2/2)\cos(\theta_2/2)) + l_3\cos(\theta_2) + 2((l_4/\theta_4)\sin(\theta_2 + (\theta_4/2))) +$$

$$l_5\cos(\theta_2+\theta_4) \quad + \quad \ldots\ldots\ldots\ldots\ldots\ldots+$$

$$2((l_{2n}/\theta_{2n})\sin(\theta_{2n}/2)\cos(\theta_2+\theta_4+\ldots\ldots(\theta_{2n}/2)))$$

$$+l_{2n+1}\cos(\theta_2+\theta_4+\ldots\ldots\theta_{2n}) \qquad (6)$$

where l_i is the length of the i^{th} element on the left hand or right hand side of the section centre line

θ_i is the angle of bending of the i^{th} element on the left hand or right hand side of the section centre line

$2n+1$ is the total number of elements (on one side of the centre line)

the permissible sideways metal movement per pass (PMM) is given by

$$PMM = L(\tan(\phi))$$

where L is the interpass length

ϕ is the maximum forming angle

thus if FACL and FACR are respectively the minimum number of passes constrained by sideways metal movement on the left hand and right side of the section

then $FACL = (DX_l/PMM)$ and $FACR = (DX_r/PMM)$ (7)

The minimum number of passes is obviously the larger value of FACL and FACR. It should be remembered , however, that this value must be modified to include the effects of springback.The method used to obtain this modified value is described below; between each pair of compulsory passes the sideways metal movement due to springback is sampled at twenty equispaced points. From these values an average sideways metal movement due to springback is calculated, for each side of the section at each compulsory pass.Thus the modified values for the minimum number of passes,considering springback,in moving between two compulsory passes are given by :

$$FACL = (DX_l/(PMM-SBL)) \qquad FACR= (DX_r/(PMM-SBR)) \qquad -(8)$$

where : SBL is the average sideways metal movement due to springback on the left hand side of the section

SBR is the average sideways metal movement due to springback on the right hand side of the section

Additionally, when producing a flower pattern, the minimum number of intermediate passes is dictated by the maximum power dissipation deemed permissible at each pass. In the limited input flower pattern program the minimum number of intermediate passes is calculated by the following method.

The plastic work done in bending (W) (per unit length) is given by the following expression[29,43].

$$W = Y(T^2/4)\theta \qquad -(9)$$

where Y is the materials yield stress

T is the materials thickness

θ is the angle of bending

therefore the work done in bending a length y is

$$W = Y(T^2/4)\theta y$$

therefore the power required in forming the bend (W) is given by

$$W = Y(T^2/4)\theta(dy/dt) \qquad - (10)$$

where (dy/dt) is the velocity of rolling

Therefore if P_{max} is the maximum permissible power dissipation per pass and FACP is the minimum number of intermediate passes (constraiined by passes)

$$FACP = W / (P_{max}) \qquad - (11)$$

The minimum number of intermediate passes is the largest value of FACL,FACR and FACP taken to the next highest integer value.Using the program, the designer is given the choice between generating the intermediate passes such that , either the increase in the angle of bending at each intermediate pass is constant or the sideways metal movement between each intermediate pass is constant.

The maximum increase in the angle of bending at any pass is constrained to be less than fifty degrees. This value was chosen since fifty degrees is the maximum angle ,obtained by practical experience, which can be formed at one pass without there being the likelihood of section defects occuring.If the proposed flower pattern includes an increase in the angle of bending greater than fifty degrees an additional intermediate pass is automatically generated.

8.6.2 INTERACTIVE FLOWER PATTERN EDITOR

The previous section described the logic by which the flower pattern is generated, the designer is next given the opportunity, at this stage, to examine the flower pattern both numerically and visually and to edit the generated flower pattern.

The editing of the flower pattern is menu driven and consists of three menus (detailed in Figure 8.12). The first menu (A) allows the designer to view the flower pattern or to view the wire frame or to examine the generated/edited flower pattern data or to enter the next menu (B) or to leave the interactive editor.

The second menu (B) gives the user the option of proceeding to the next menu (C) or to return to menu (A) with or without updating the flower pattern to include any editing which may have taken place. The third menu (C) contains editing facilities, similar to many text editors, allowing the user to alter the values for any bend at any stage, to insert new lines of text or to delete existing lines of text. Additionally the user can list the edited text or return to menu (B).

MENU A
======

PLEASE INPUT 1-5

1 TO PLOT FLOWER PATTERN
2 TO RUN WIRE FRAME VIEW
3 TO EXAMINE FLOWER PATTERN DATA
4 TO EDIT FLOWER PATTERN DATA
5 TO FINISH SESSION

MENU B
======

PLEASE INPUT 1-3
1 TO EDIT FLOWER PATTERN
2 TO EXIT EDITOR WITHOUT UPDATING
3 TO EXIT EDITOR AND UPDATE

MENU C
======

EDITING OPTIONS
PLEASE INPUT 1-4

1 TO INPUT A NEW PASS
2 TO DELETE A EXISTING PASS
3 TO ALTER A EXISTING PASS
4 TO FINISH EDITING

FIGURE 8.12 FLOWER PATTERN EDITOR MENU

8.6.3 AUTOMATIC PERCENTAGE COMPOSITE ELEMENT LENGTH

Having examined and, if necessary, edited the generated flower pattern, the user enters the third section of the program, which contains the means of controlling the forming of bends. The automatic percentage composite element length option, described in section 4.4, is used to control the radius of forming and hence generate the required percentage element lengths.

8.7 DISCUSSION ON THE APPLICATION OF THE COMPUTER TO FORM ROLL DESIGN

The previous chapters have described two complementary approachs to the problem of achieving consistently effective form roll design. Namely, generation of form roll design and analysis of form roll design. Both have evolved from the CAD/CAM system and hence have approached the problem by considering the methods by which the computer can aid form roll design. It is felt that these two approachs are equally legitimate and should continue in parallel. It will, perhaps be enlightening at this stage to review the present state and limitations of these two approachs.

Considering generation of form roll design , the conventional theory comprises of the forming angle theory, within this chapter new concepts have been introduced such as those of compulsory passes and maximum positions, a new theory has been developed for generating the means of forming the bends and the designers experience has been included by specifying the maximum permissible metal movement, power, springback and increment of angle.

Considering the analysis of form roll design. Visually, a comprehensive series of new techniques have been developed for the visual analysis of form roll design. Numerically, the minimum energy technique has been extended, it is believed for the first time, to the general case for the analysis of form roll design.

In general then, the existing knowledge, relevant to the form roll design process, has been included in the software and additional techniques have been developed and incorporated into the CAD/CAM system. However, whilst significant advances have been made,it has become apparent that a major limiting factor in the future application of the computer to form roll design is the limit of knowledge of the form rolling process and the effect of form roll design in particular. This leads to the inevitable conclusion that, in the near future, a prerequisite to further CAD research will be experimental research into the cold roll forming process. Hence, the following chapter will describe a method for the analysis of form roll design and some initial results.

CHAPTER 9

EXPERIMENTAL ANALYSIS OF FORM ROLL DESIGN

9.1 INTRODUCTION

This chapter is concerned with experimental determination of the shape of metal and the distribution of longitudinal strain between successive passes . Before proceeding with the study it was necessary to decide on the type of section to investigate and the material (or materials) to employ. Also it was necessary to decide on the data which was to be collected and the best means of collecting this data.

9.2 CHOICE OF SECTION

It immediately became apparent that it would be necessary to investigate the roll forming of a simple section, since, as the complexity of the section increases, the cost of producing rolls and the time spent in setting and rolling would rapidly become prohibitively large. It was decided, then, to investigate the cold roll forming of channel sections. The channel section provides three easily variable parameters, thickness, leg length and radius of bending (where Figure 9.1 illustrates what is meant by these three terms). Additionally, the simple shape of the section allows reasonable ease of access (for measuring strain) over the whole of the profile. Finally, it was possible to borrow a set of universal channel rolls which greatly reduced the cost of manufacturing the rolls.

It was decided to examine three values of each of the three parameters, thus making a total of 27 (3x3x3) permutations. Table 9.1 describes the values of each of these three parameters chosen.

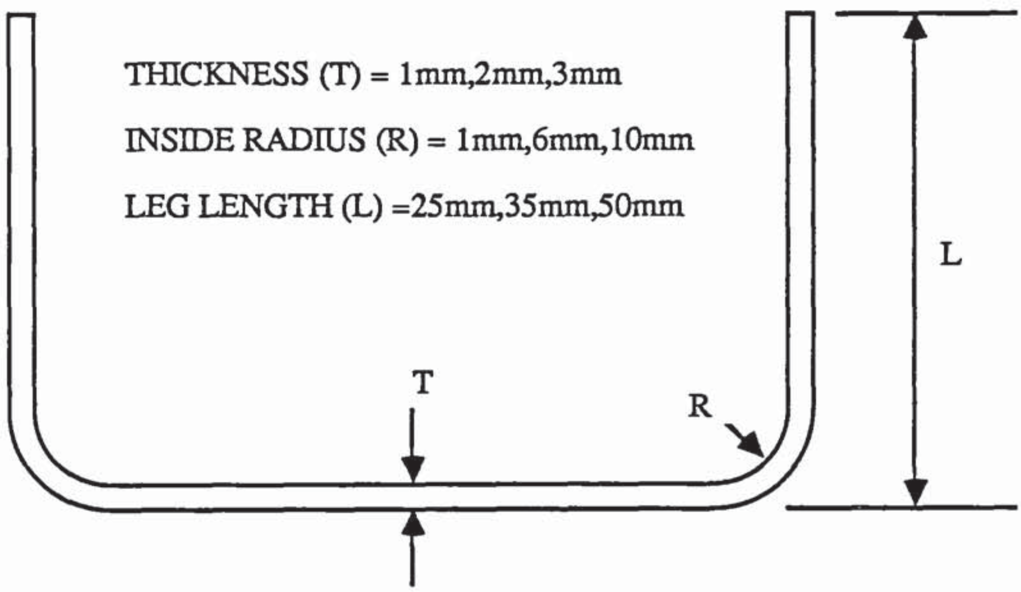


FIGURE 9.1 TERMS DEFINING THE CHANNEL SECTION

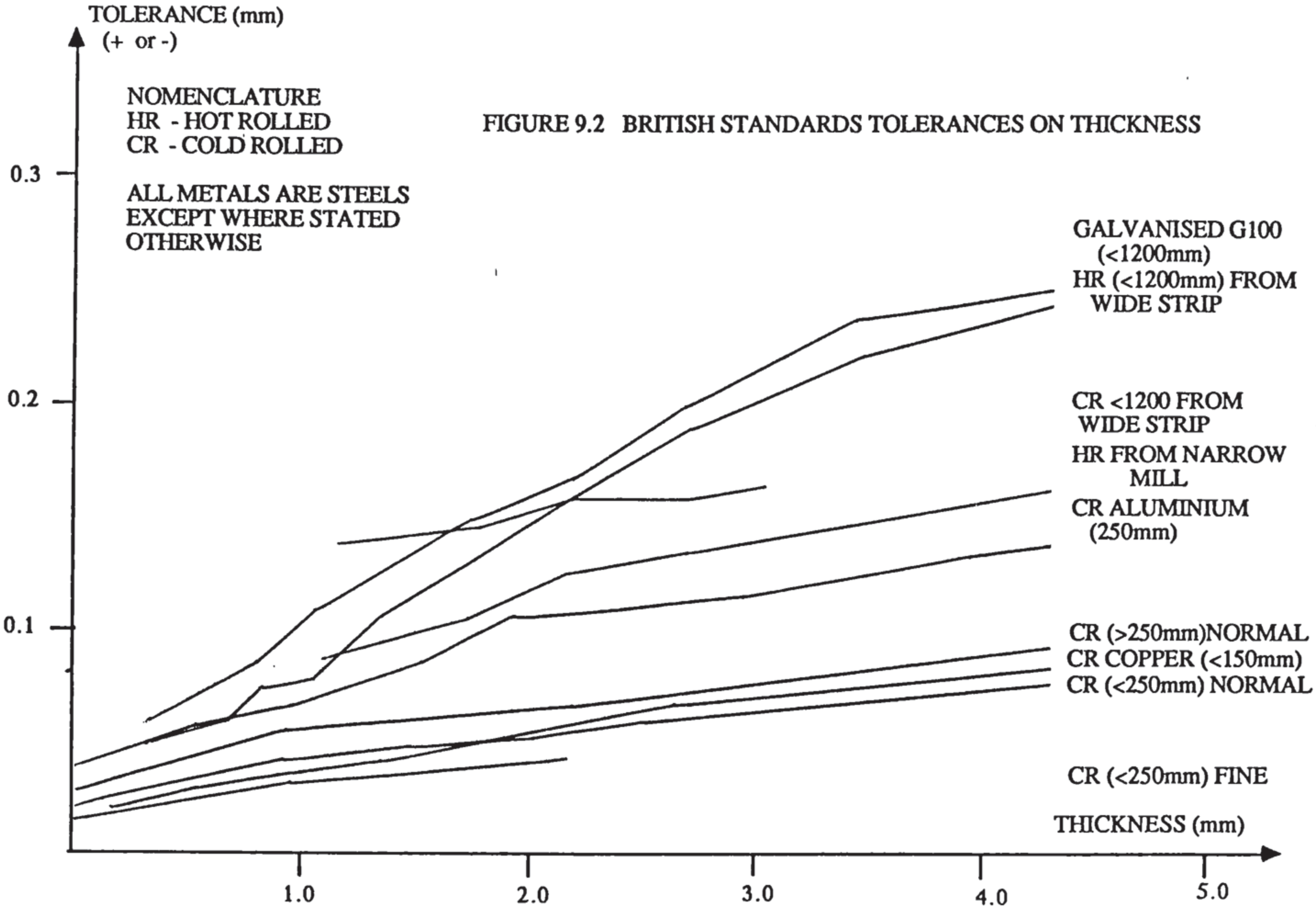
THICKNESS (T)	1mm,2mm,3mm
INSIDE RADIUS (R)	1mm,6mm,10mm
LEG LENGTH (L)	25mm,35mm,50mm

TABLE 9.1 EXPERIMENTAL PARAMETERS

In general, the upper value of the three parameters was selected to make the range of the parameters as large as the process permitted. The upper value of thickness was chosen, after practical advice, as being the thickest metal which could reasonably be rolled using the available mill. The upper value of inside radius was chosen so that the estimated springback for the worst case (R=10,T=1) would still be around 1%. The upper value of leg length was restricted by the maximum leg length which could be rolled using the universal channel rolls. The lower value of inside radius was dictated by the minimum value that could be rolled without tearing occuring at the outside edge using the maximum thickness of metal.

On a test run, using a galvanized steel sheet, it was found that one of the major limitations on the measurement of strain was the legibility of the grid pattern machined onto the specimen. Using the galvanized steel it was found that variation in the sheet thickness was a major contributory factor to the accuracy of measuring strain, since, as the depth of cut increased the centre of the machined line or circle become indistinguishable. Therefore, of the common sheet metals, the one with the tightest dimensional tolerance on thickness was chosen. Considering Figure 9.2, (the relative British Standard tolerances for

FIGURE 9.2 BRITISH STANDARDS TOLERANCES ON THICKNESS



thickness), it can be seen that the cold rolled steels, in general, form the group with the tightest tolerances. Therefore a cold rolled steel (CR3) was eventually chosen to form the test material.

9.3 SCRIBING OF GRID

As the first step in measuring the strain distribution through the cold roll forming process a number of specimens were marked out with a grid of a known pattern. The deformation could then be estimated by measuring the grid after removal from the mill. From preliminary work it was known that the longitudinal strain would be small, probably at maximum one to two percent. Additionally it was known that as the longitudinal strain decreased, the experimental error, due to marking out and measuring, became proportionally more important. Therefore, only the largest of the three leg lengths were marked out in this fashion, since it was felt that for the two smaller leg lengths, the values of longitudinal strain would be so small that the experimental error would become a significant factor.

It was decided to use a Bridgeport series 1 interact numerically controlled milling machine[61] to mark the prescribed pattern. The machining set up is summarised in Figure 9.3 and is briefly described below. Firstly, two steel cylinders were clamped to the workpiece table and a milling cutter run along their faces parallel to the y axis; this ensured that the metal strips (when pushed tightly against the cylinders) were parallel to the y axis. Secondly, a magnetic table was clamped to the machine table. Thirdly, the metal was clamped either side of the magnetic table using steel parallels. Finally, a scribing tool was mounted in the milling machine spindle.

A number of likely grid patterns were tested (Figures 9.4A and 9.4B) prior to the tests and the following points were noted.

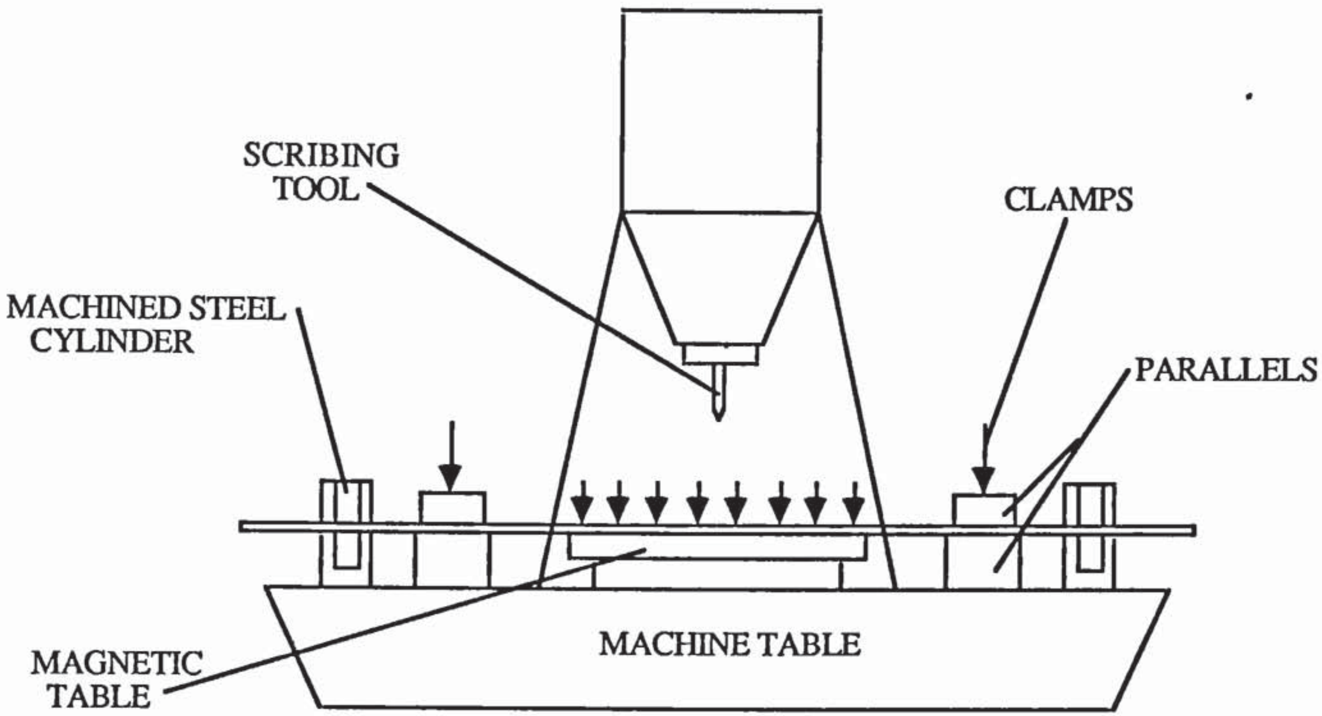


FIGURE 9.3 MACHINING SETUP FOR SCRIBING GRID

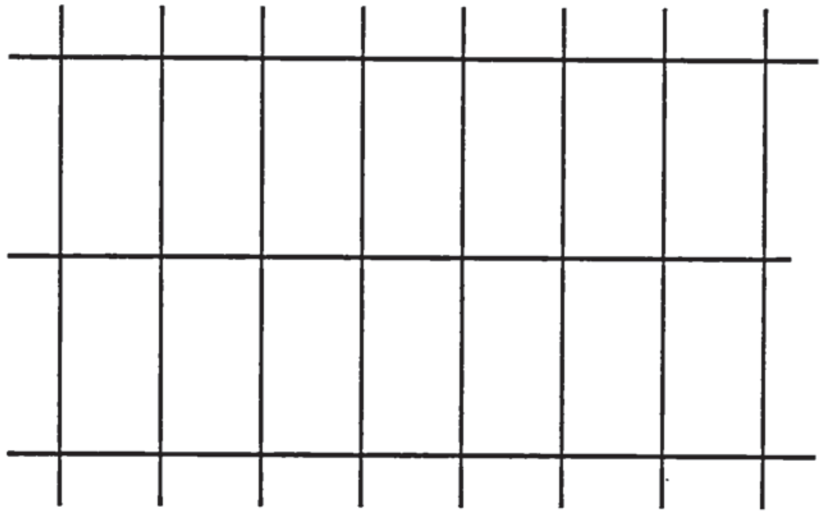


FIGURE 9.4A RECTANGULAR GRID PATTERN

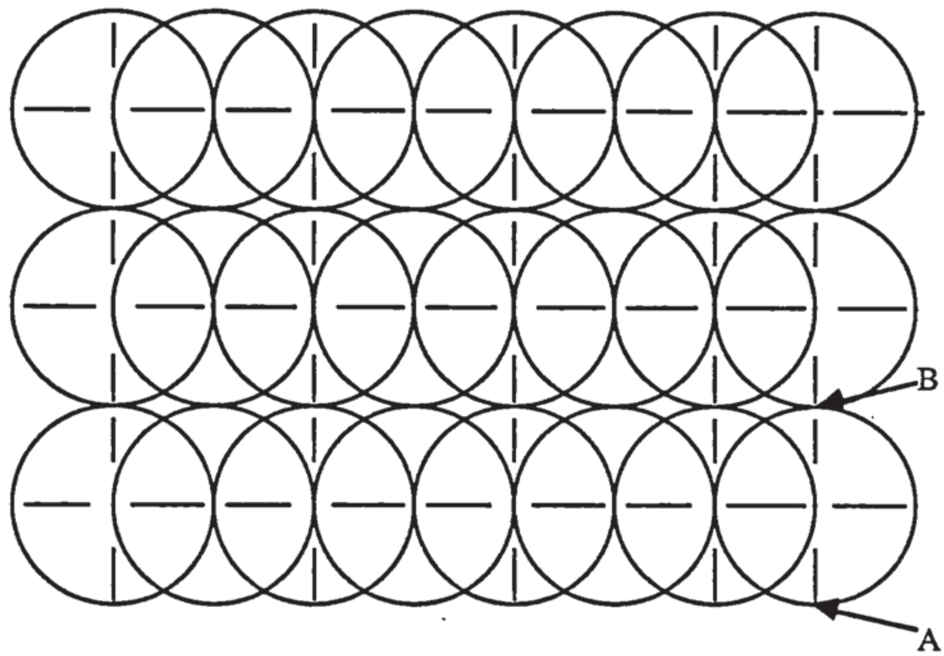


FIGURE 9.4B CIRCULAR GRID PATTERN

(I) The quality of the scribed line was heavily dependent on the sharpness of the scribing tool. When the tool had been recently reground there was a definite "bottom" to the scribed line. When the tool was blunt it was difficult to discern the actual line from the surrounding debris.

(II) The quality of the scribed line was heavily dependent on the depth of cut, the smaller the depth of cut the more clearly the centre of the line could be seen.

(III) Scribed lines could easily be destroyed by debris from adjacent scribed lines, this was particularly important when lines were scribed in the manner shown in Figure 9.4B. For instance it would be difficult to measure from point A to point B at the required accuracy.

(IV) The direction of cutting was extremely important since the debris was not evenly distributed on opposite sides of the tool. Therefore when the tool lost its original sharpness it became very difficult to estimate the centre of the line.

(V) The length of time to machine the circular grid (Figure 9.4B) was exceedingly large.

Considering the factors listed above it was decided to use a grid such as the one shown in Figure 9.5. This pattern comprised a series of "dots" where each dot represented the intersection of two perpendicular lines in a grid such as Figure 9.4A. This had the advantages that, the debris did not affect the quality of scribing, the scribing tool remained sharp since very little metal was being removed, the direction of cutting is unimportant using such a pattern and also the scribing of nine specimens could be achieved in a reasonable time. The grid was machined to the dimensions described in Figure 9.5. The values $P_1 : P_{19}$ varied with the value of the inside radius , according to Table 9.2.

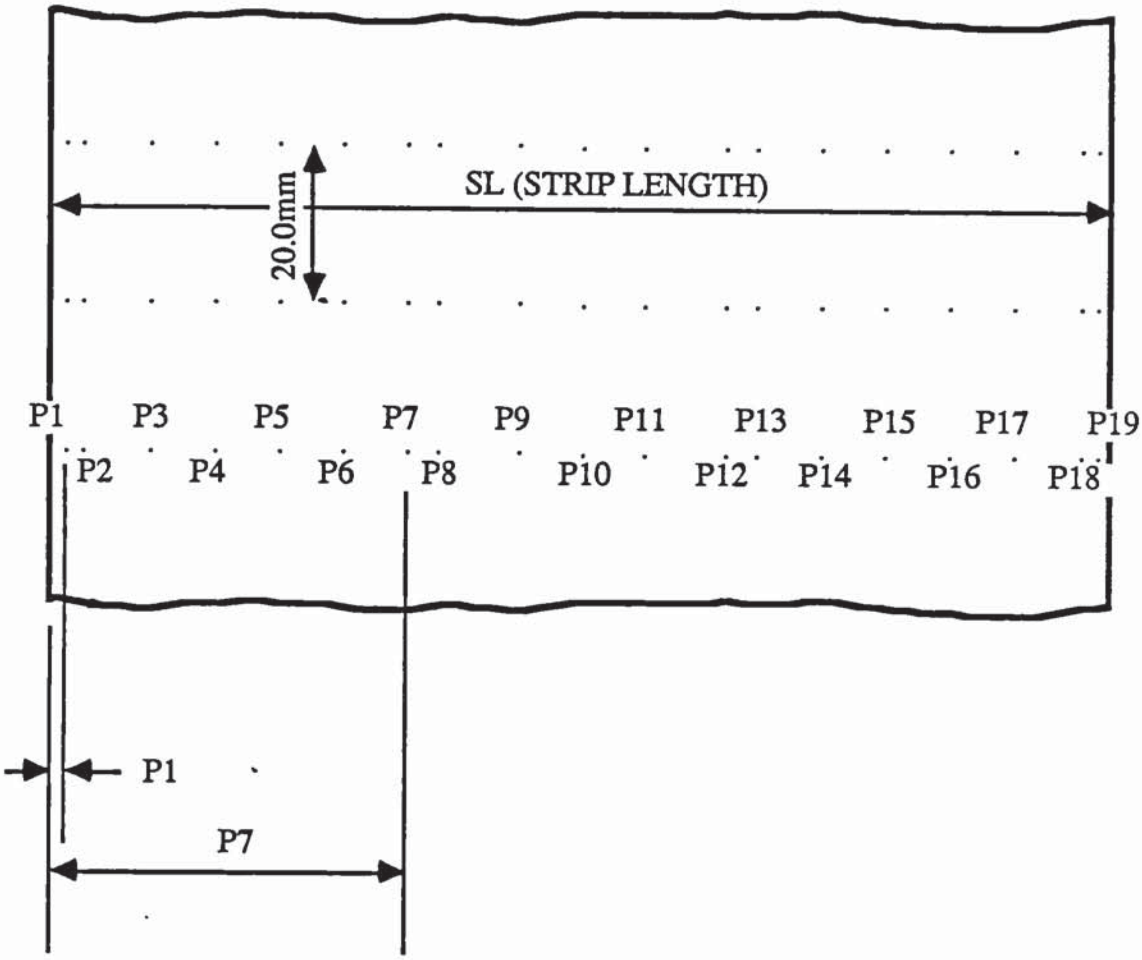


FIGURE 9.5 THE FINAL GRID PATTERN

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
R=1	2.0	4.0	12.0	20.0	28.0	36.0	44.0	49.5	58.5	66.5
R=6	2.0	4.0	12.0	20.0	28.0	36.0	44.0	48.5	56.5	64.5
R=10	2.0	4.0	12.0	20.0	28.0	36.0	44.0	47.5	54.5	62.5

	P11	P12	P13	P14	P15	P16	P17	P18	P19	SL
R=1	74.5	83.5	89.0	97.0	105.0	113.0	121.0	129.0	131.0	133.0
R=6	72.5	80.5	85.0	93.0	101.0	109.0	117.0	125.0	127.0	129.0
R=10	70.5	77.5	81.0	89.0	97.0	105.0	113.0	121.0	123.0	125.0

TABLE 9.2 DIMENSIONS OF MACHINED GRID
(all dimensions in mm)

P_{10} represents the centre line of the section and the scribed points are symmetrical about this line. P_8 and P_{12} are points on the circular elements of the section. The distance between P_1 / P_2 and P_{18} / P_{19} was set at 2mm, this was because it was felt that the strain at the edge of the strip would be particularly interesting and thus the first and last points should be as close as possible to the strip edge. There was also a danger that P_1 and P_{19}

would be destroyed by contact with the strip checks on the rolls and so P_2 and P_{18} were included as a safeguard against this eventuality.

Along the length of the strip, lines of points were seperated by a constant distance of 20.0mm. The N.C program for cutting a grid over 240mm of the sheet is described in Appendix E. Each specimen was marked out for a total of approximately 1000mm, where the distance from the end of the marking out to the end of the strip was approximately 150mm.

9.4 THE MACHINE TRIALS

This section is concerned with the planning and execution of the machine trials. With the cost of running a rolling mill being approximately £40 per hour it is vital that the planning stage is carried out as effectively as possible, leaving as little work as possible to the execution stage.

9.4.1 PLANNING FOR THE MACHINE TRIALS

There were two factors which were considered particularly important in the planning stage ; namely :

(1) The longitudinal strain in the sections should be made as large as possible so that the measured values of longitudinal strain would become large compared to the errors due to marking out and measuring.

(2) The number of new rolls to be manufactured and the amount of time spent on the mill should be minimised such that the costs were kept to a reasonable level.

The longitudinal strain was increased by choosing a rolling mill with the minimum inter pass distance and by reducing the number of passes to form the section to a minimum. It was decided that the minimum possible number of passes which could reasonably be considered was three, where the complete flower pattern is given in Figure 9.6.

The number of new rolls needing to be machined was reduced to nine, with only the top rolls requiring to be machined specifically for the trials. The bottom rolls and the side rolls (for the final pass) were borrowed from a set of universal channel rolls. Where universal channel rolls are rolls which are split so that the base width can be varied by inserting 'spacers'. The leg length can similarly be varied such that legs up to 50mm can be rolled. Initially, for each thickness of material the three top rolls were manufactured for the sections with the smallest inside radius. When all of the sections with the smallest inside radius had been rolled the radius could be remachined to the medium (6mm) inside radius (Figure 9.7) and when all of the sections with the medium inside radius had been rolled the rolls were remachined to the largest inside radius.

The general roll design is detailed in Figure 9.8 , where the values for the pass heights and the roll centre to centre distances for each trial are contained in to Table 9.3.

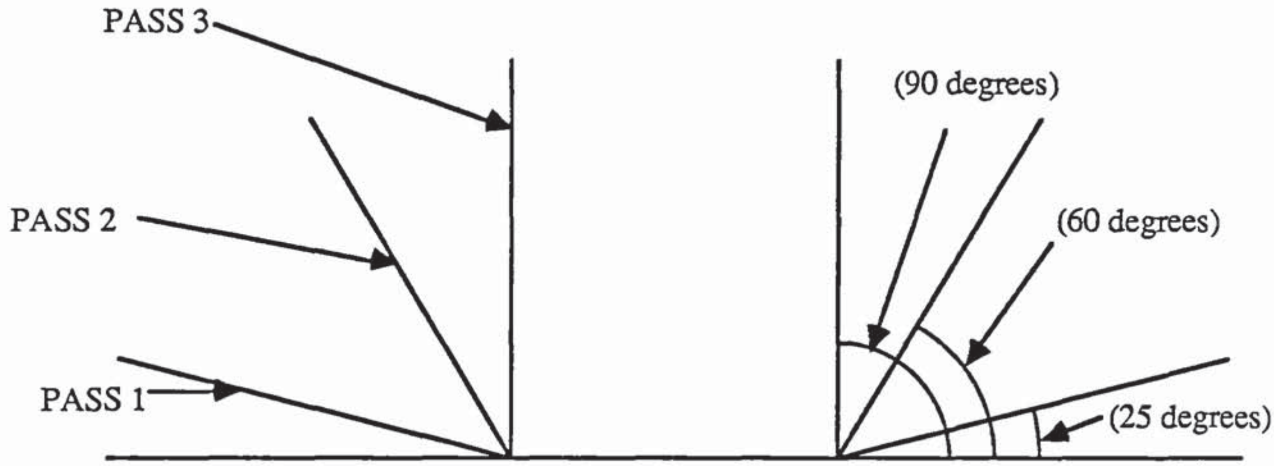


FIGURE 9.6 FLOWER OF SPECIMENS FOR MACHINE TRIALS

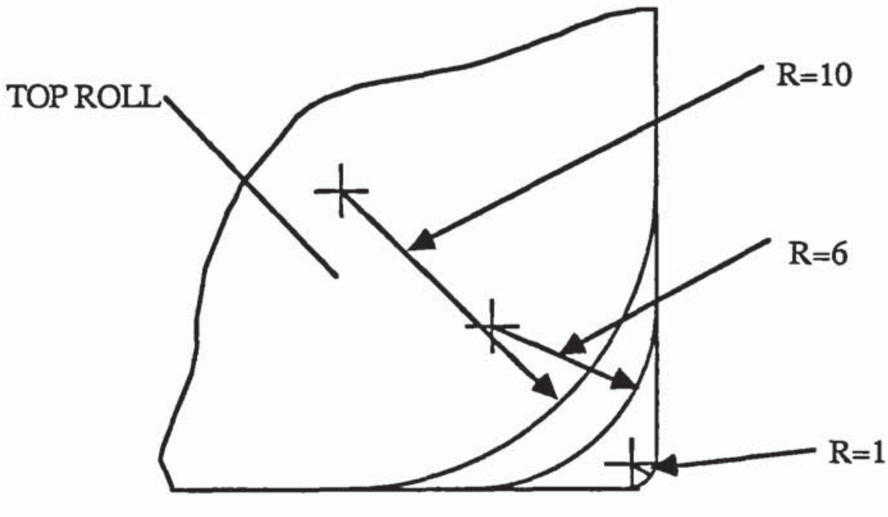
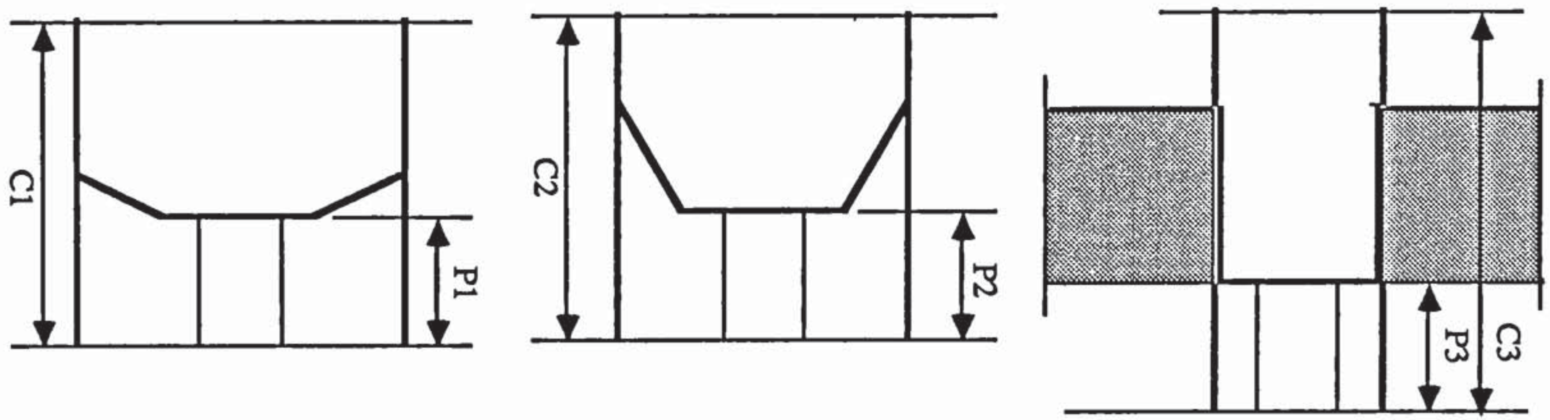


FIGURE 9.7 VARYING THE INSIDE RADIUS OF THE TOP ROLL BY REMACHINING



PASS 1 (25 degrees) PASS 2 (60degrees) PASS 3 (90 degrees)

FIGURE 9.8 DEFINITION OF ROLL DIMENSIONS

	P1	C1	P2	C2	P3	C3
T=1	53.34	122.9	53.34	146.3	53.98	153.3
T=2	53.34	123.9	53.34	147.2	53.98	155.2
T=3	53.34	124.9	53.34	148.3	53.98	155.2

TABLE 9.3 PASS HEIGHTS AND ROLL CENTRE TO CENTRE DISTANCES

It was hoped that by careful sequencing of the machine trials the setting times could be reduced . To achieve this , groups of trials with the same thickness and inside radius were conducted consecutively, by performing the tests in this order the rolls only needed to be realigned for one in three tests.

9.4.2 OBTAINING THE DEFORMED SPECIMENS

The deformed specimens were obtained using a rolling mill situated at Hadley Industries Ltd, Smethwick, Birmingham. The interpass forming distance was approximately 240mm and the specimens were rolled without using any form of lubrication. Prior to rolling the actual specimens two dummy specimens were passed through the mill to allow the correct setting to be obtained (where correct was taken as meaning that the leg lengths were equal and the specimen was as straight as could be achieved).

With the actual specimen, the mill was stopped whilst the scribed portion of the specimen was between the passes and on the outside of the section. The top rolls were then removed and the deformed specimen was lifted out of the mill.

9.5 MEASUREMENT OF DEFORMED STRIP

The product of the machine trials were 27 deformed strips or tags. Any tag is going to be a complex three dimensional shape, therefore the measurement of the deformed grid required the use of some form of three dimensional measuring device. In this case it was decided to use a Societe Genevoise optical jig borer (model 2P) with a tool makers microscope mounted in the spindle for measuring the deformed metal shape. This provided not only the ability to measure in three dimensions but also ,importantly,was large enough to accommodate the deformed strip.

The jig borer is a precision machine tool where the accuracy in the horizontal plane is guaranteed to .002mm. When measuring in three dimensions the Z coordinate can be obtained by focusing onto the surface of the deformed strip. Therefore, when the microscope cross hairs are positioned over a machined "dot" and the "dot" is in focus the 3 dimensional coordinate of the point is obtained.

From the 27 deformed strips there were an immense number of possible measurements which could be taken defining shape and strain. Since each 3 dimensional reading took approximately 3-5 minutes to complete and on each specimen there were approximately 1000 points it immediately became apparent that it was necessary to be selective about the measurements which were taken. It was decided that the following representative groups of readings should be considered.

(1) The plan view of all 27 deformed sheets was obtained. This would give an idea of the distribution of deformation in the 27 tags. The plan views were obtained as follows (with reference to Figure 9.9). The points A_1, A_2, A_3 etc were obtained

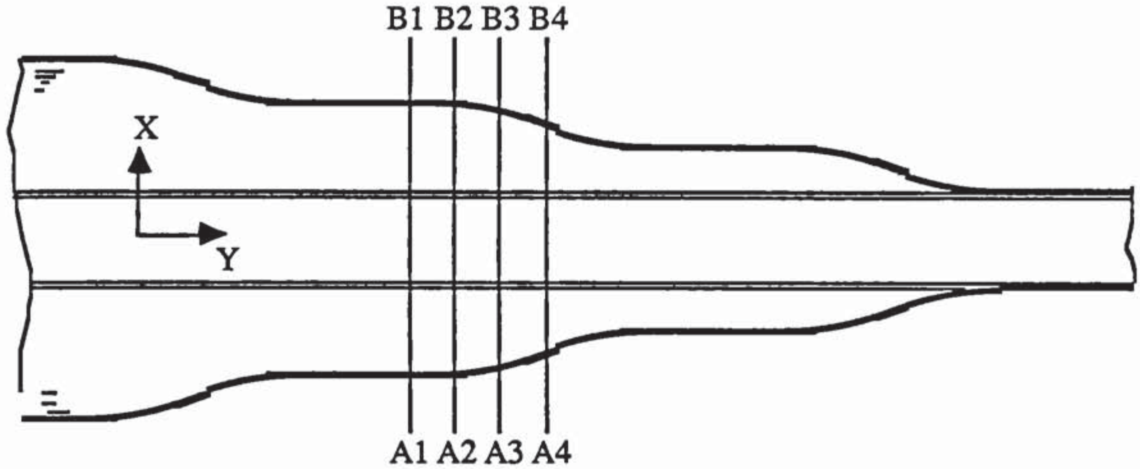


FIG 9.9 MEASUREMENT OF METAL SHAPE

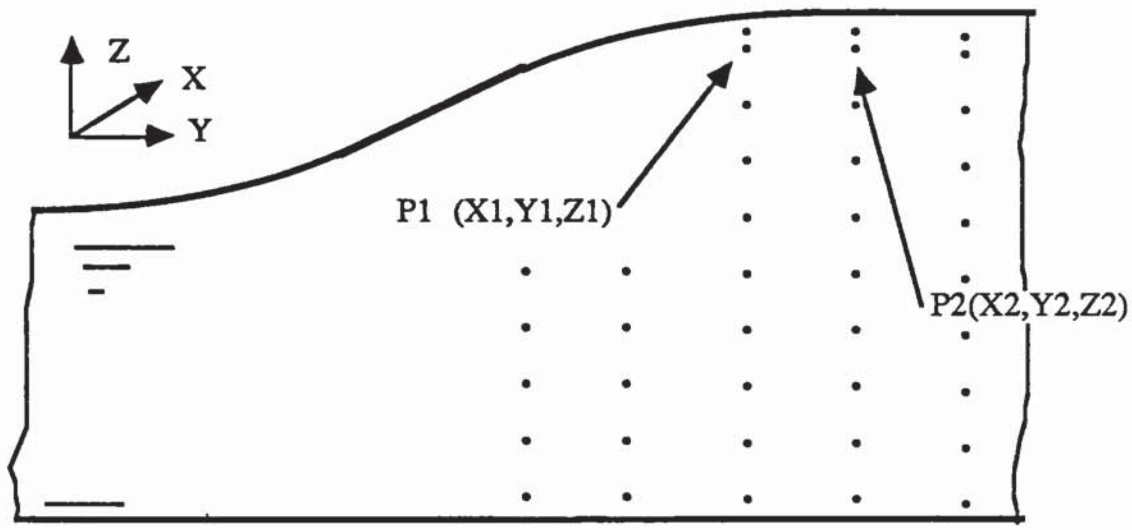


FIGURE 9.10 MEASUREMENT OF LONGITUDINAL STRAIN

and then the points B_1,B_2,B_3 etc were obtained and hence the width of the channel was estimated at various positions (every 25mm) along the deformed strips length.

(2) For the 9 specimens of leg length 50mm, the longitudinal strain along each edge was obtained.

(3) For the 3 specimens of leg length 50mm and inside radius 1mm the entire longitudinal strain field was obtained for the second and third passes. The sections with the smallest inside radius were chosen for the most detailed study because it was known that the springback would be less and hence the measured strains would be closest to those occuring during rolling.

The strain in the region between two points was calculated by the method described below (with respect to Figure 9.10). The three dimensional coordinates of P_1 and P_2 were measured using the jig borer and since it was known that the two points P_1 (X_1,Y_1,Z_1) and P_2 (X_2,Y_2,Z_2) were originally 20.0mm apart therefore the longitudinal strain could be calculated using the expression below.

$$\text{Longitudinal strain} = (\sqrt{((X_2-X_1)^2+(Y_2-Y_1)^2+(Z_2-Z_1)^2)}-20.0)/20.0$$

9.6 RESULTS OF MACHINE TRIALS

As was mentioned previously, the data collected from the deformed specimens falls into three main groups. Namely :

(I) Data defining the geometry of the deformed specimens.

(II) The edge strain of the deformed specimens.

(III) The total longitudinal strain distribution of the deformed specimens.

9.6.1 SHAPE OF THE DEFORMED SPECIMENS

As was discussed in the previous section, the parameter chosen to measure and define the deformed shape was the width of the channel. Clearly, as the width of the section alters then forming must be taking place. Figure 9.11 shows a plan view of the deformed specimens, where the plan view refers to a view looking vertically down onto the deformed specimens ,(since the channel is assumed to be symmetrical it is only necessary to consider half of the section). From inspection of Figure 9.11 it is possible to make the following observations.

(I) In general, the edge of the specimens follow a path which can be idealised into that shown in Figure 9.12.

(II) With reference to Figure 9.11 and Figure 9.12 it will be seen that as the leg length increases the distance over which deformation occurs (the distance marked 'D' in Figure 9.12) increases. This agrees with the theoretical determination of the deformation length described in Section 6.5.

(III) Since the deformation length is dependent on the leg length, the severity of forming is not dependent purely on metal movement, as is commonly assumed.

The severity of forming can be illustrated by considering the gradient of the edge of the deformed specimens. (The parameter marked DY/DX in Figure 9.12). Figure 9.13 illustrates the edge gradients of the 27 deformed specimens where the gradients are shown in three main groups representing the three leg lengths. The following points can be noted from Figure 9.13.

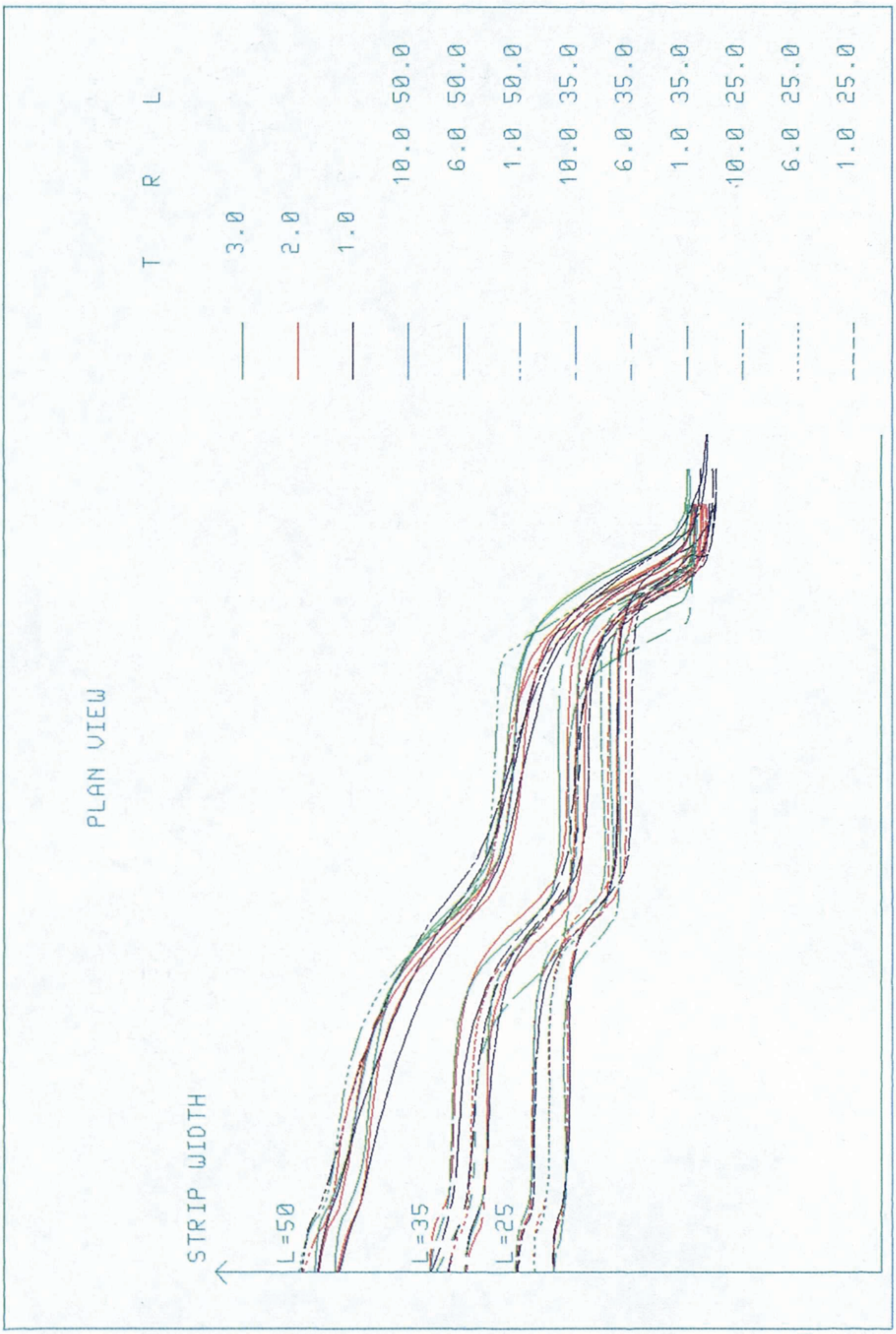


Figure 9.11 Plain view of deformed specimen

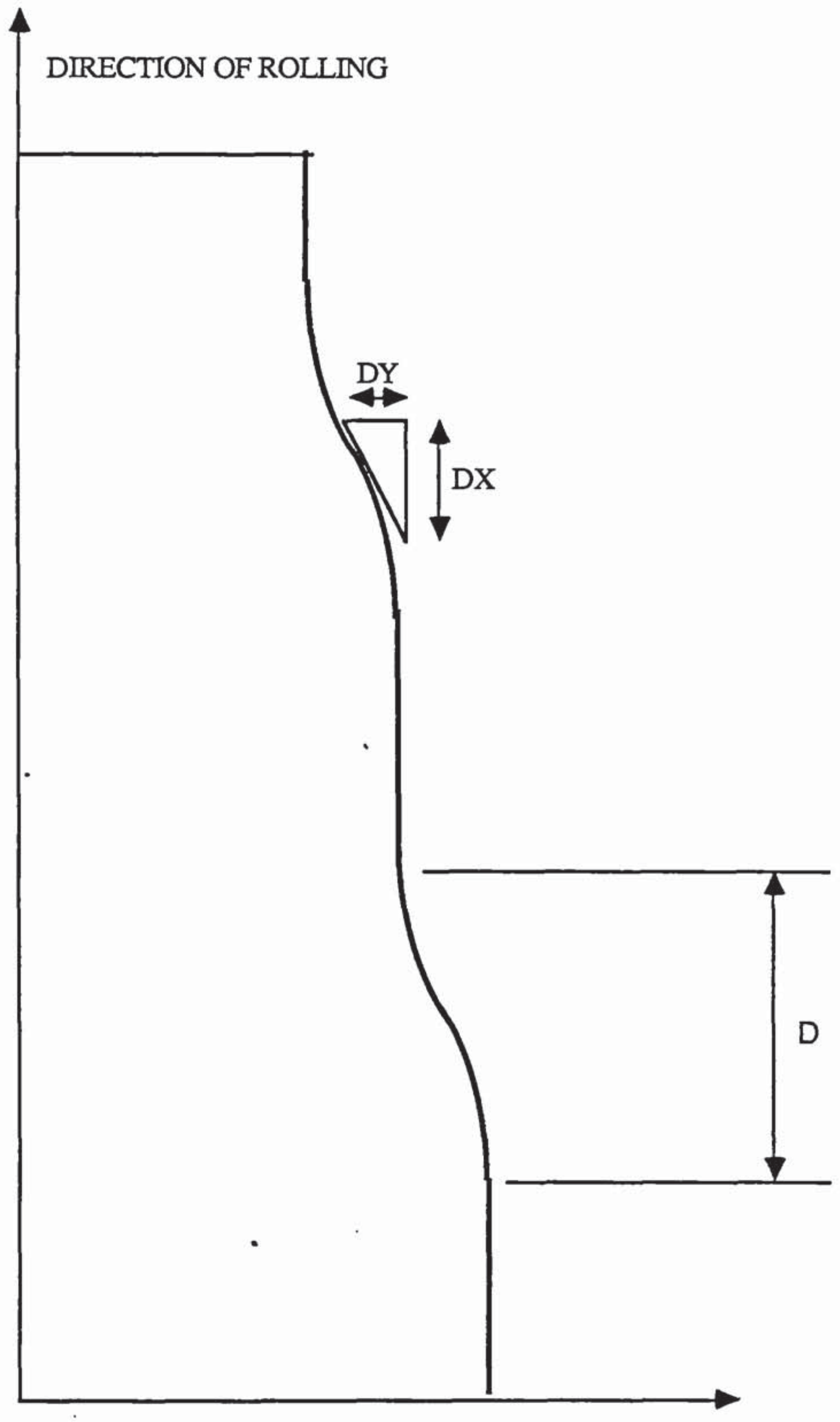


FIGURE 9.12 IDEALISED EDGE SHAPE

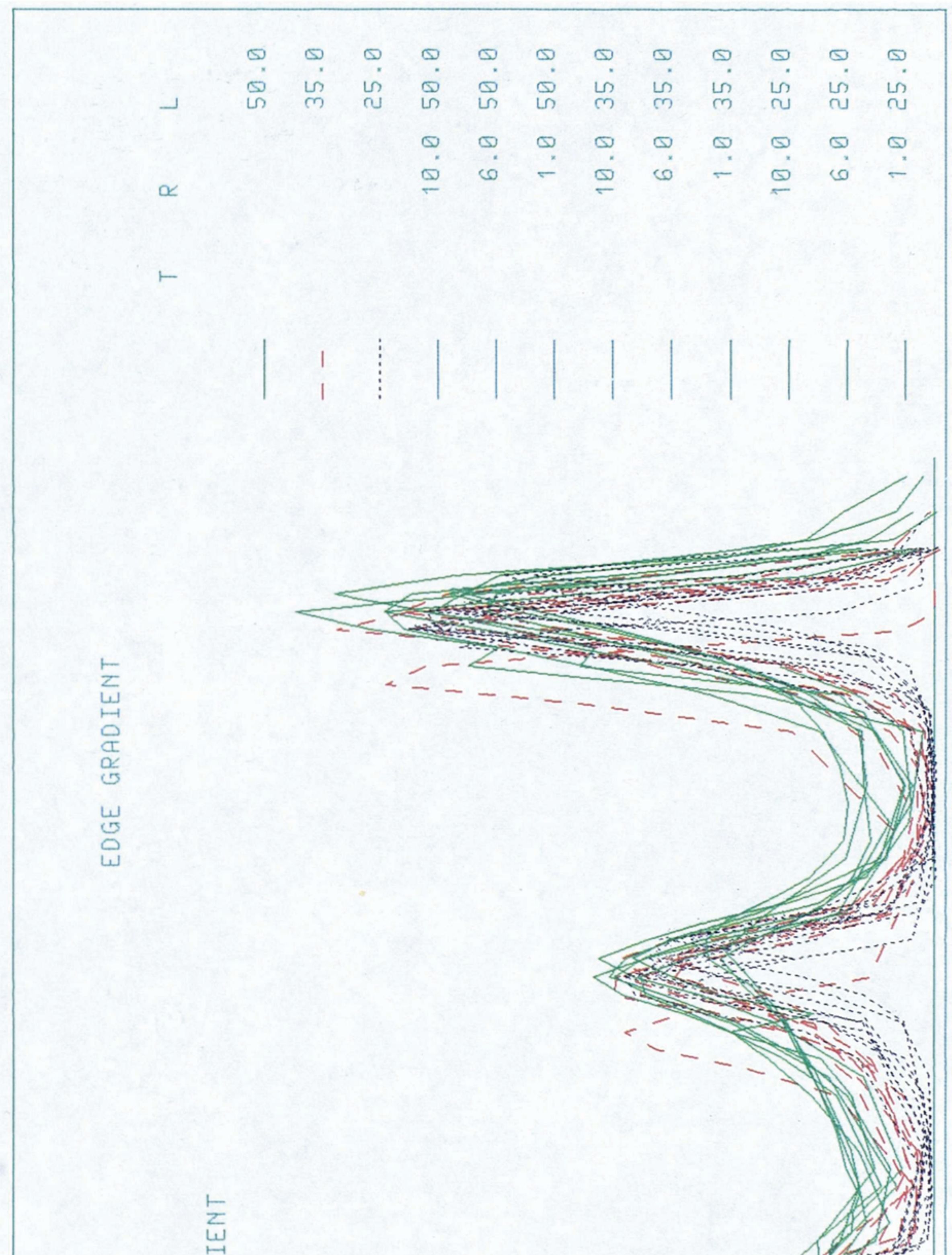


Figure 9.13 Edge gradient of deformed specimens, divided into group by leg length

(I) The sideways metal movement is more evenly distributed in the sections of greater leg length.

(II) Whilst, the maximum edge gradient increases as the leg length increases the difference is small when compared to the difference in metal movement.

Figure 9.14 illustrates the edge gradients of the 27 deformed specimens, where the edge gradients are shown in three main groups representing the three thicknesses. By inspection it can be noted that as the thickness increases the maximum edge gradient increases. Hence it would appear that as the thickness increases the severity of forming increases.

Figure 9.15 illustrates the edge gradients of the 27 deformed specimens where the gradients are shown in three main groups representing the three inside radii. By inspection it will be noted that there is no clear relationship between inside radius and edge gradient hence it would appear that thickness and leg length are the more important influences on the severity of forming.

Where the width of the specimens are known it is also possible to estimate the angle of bending (by geometry). Since the width of the specimen is known at various points along its length it is possible to estimate the distribution of angle of bending. Figure 9.16 shows the distribution of the angle of bending.

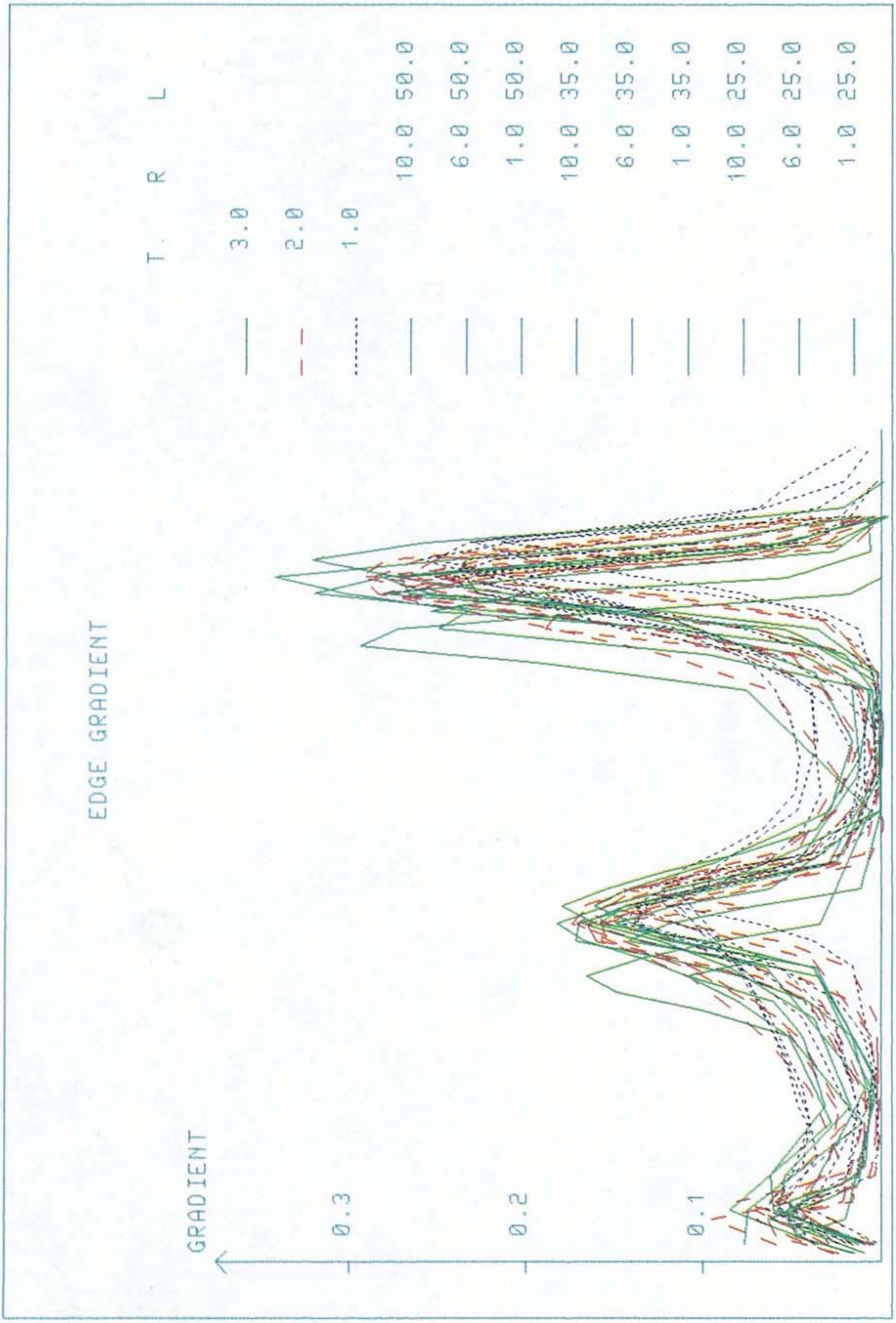


Figure 9.14 Edge gradient of deformed specimens, divided into group by thickness

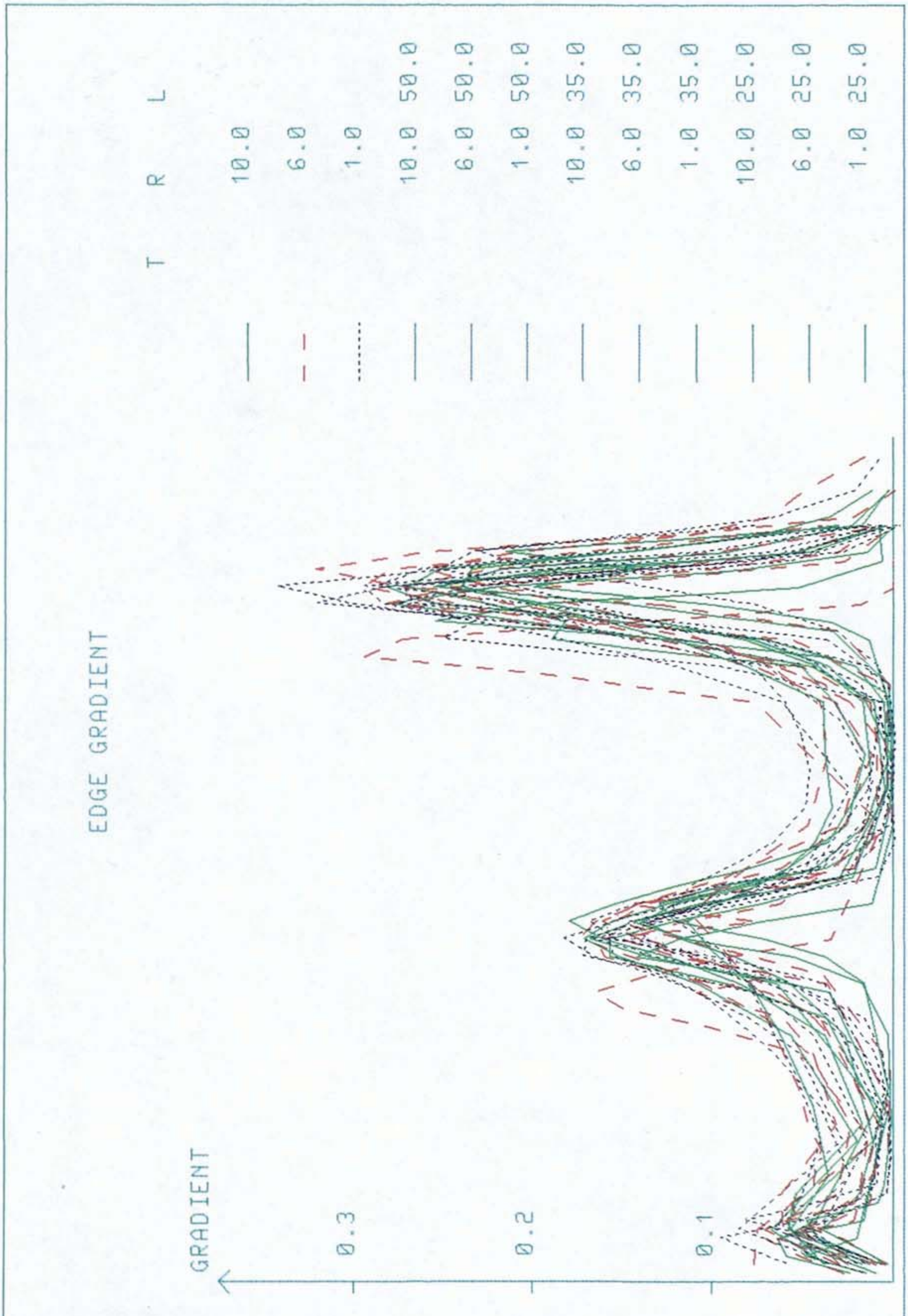


Figure 9.15 Edge gradient of deformed specimens, divided into group by inside radius

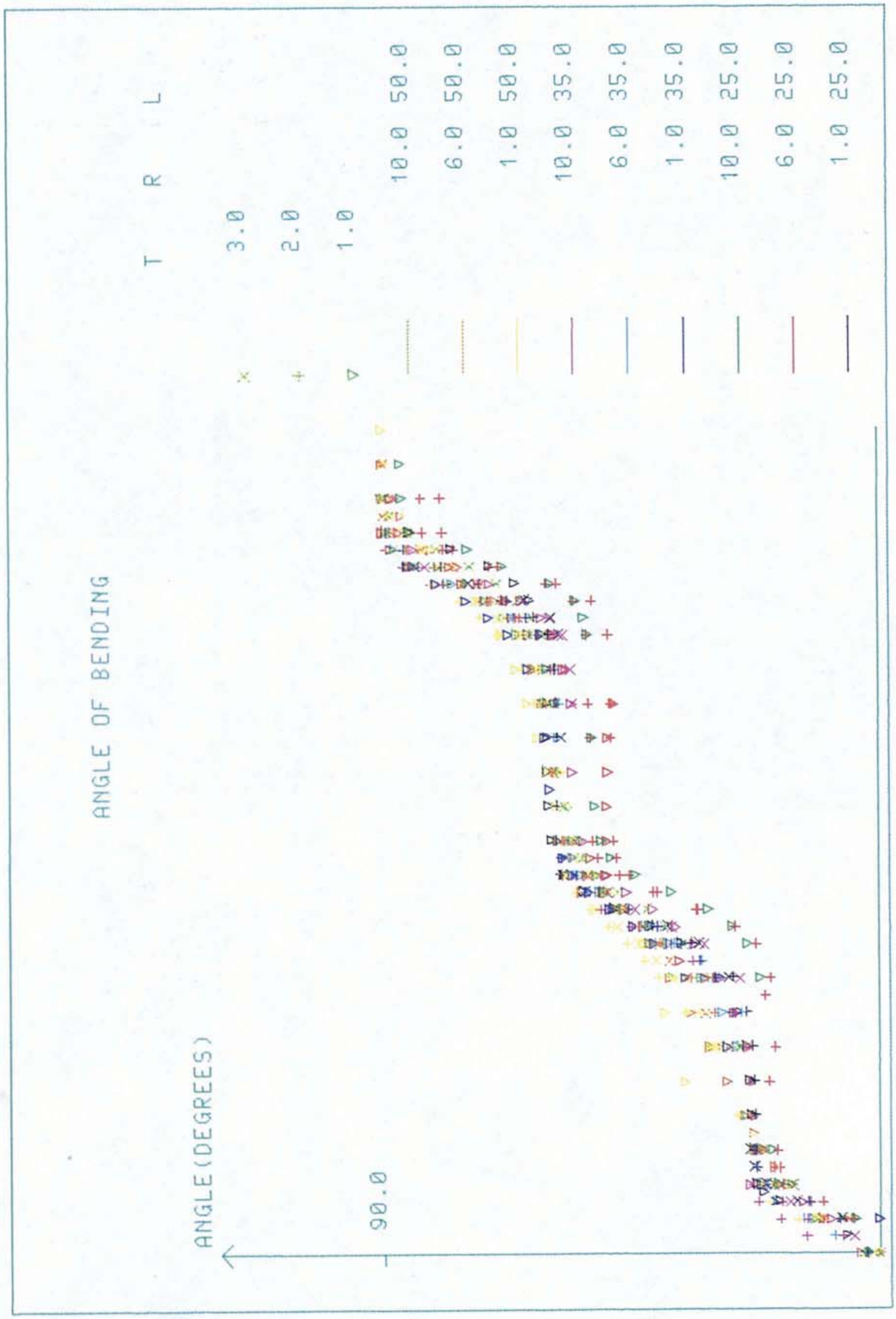


Figure 9.16 Distribution of angle of bending

9.6.2 EDGE STRAIN OF THE DEFORMED SPECIMEN

The longitudinal straining is largest, and hence most interesting, at the edge of the strip, therefore the edge strains were obtained for all nine of the prescribed specimens. Two complete sets of values were obtained for each specimen corresponding to the left hand and right hand side of the section. Theoretically, since the sections are symmetrical, the two sets of values should be roughly identical. However, in practice, particularly since the measured values of strain are small (around 1% - 2%) the experimental inaccuracy and the nature of the process itself causes a divergence between the two sets of value.

By considering the nine sets of results independently it is difficult to identify the underlying trend from the noisy data. However by plotting all nine sets of edge strain data simultaneously (Figure 9.17) the underlying trend becomes apparent. Considering Figure 9.17 , in general, the edge strains appear to follow a pattern which can be idealised as Figure 9.18.

Figure 9.19 shows the edge strains of the nine specimens, where the edge strains are shown in three main groups representing the three thicknesses. By inspection it can be noted that as the thickness increases the maximum edge strain increases. Similarly, as the thickness increases the minimum edge strain becomes smaller.

Figure 9.20 shows the edge strains of the nine specimens where the edge strains are shown in three main groups representing the three inside radii. By inspection it can be noted that there would appear to be no clear relationship between inside radius and edge strain. It would appear ,then, that the thickness is the more important influence on the magnitude of edge strain.

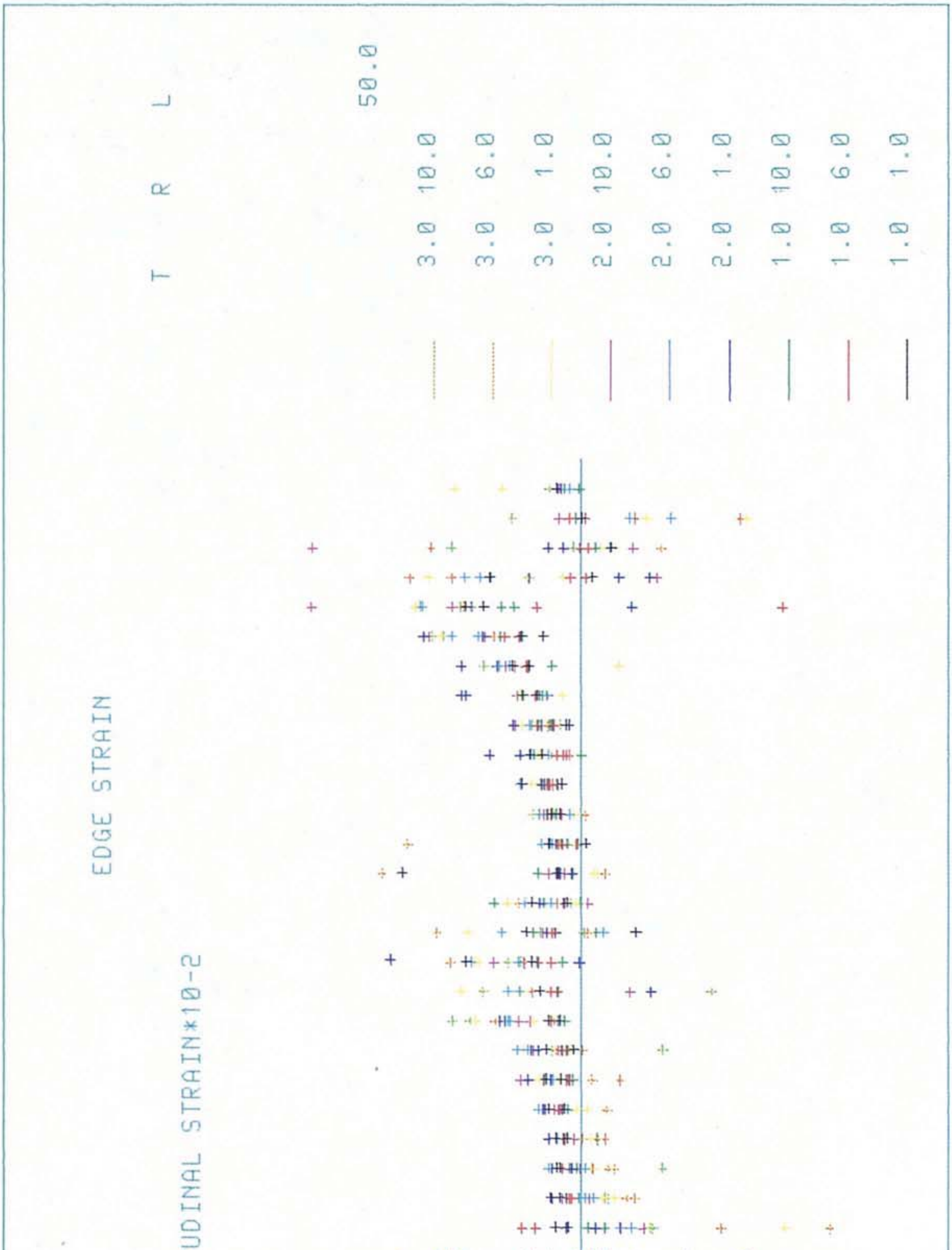


Figure 9.17 Cumulative plot of edge strains

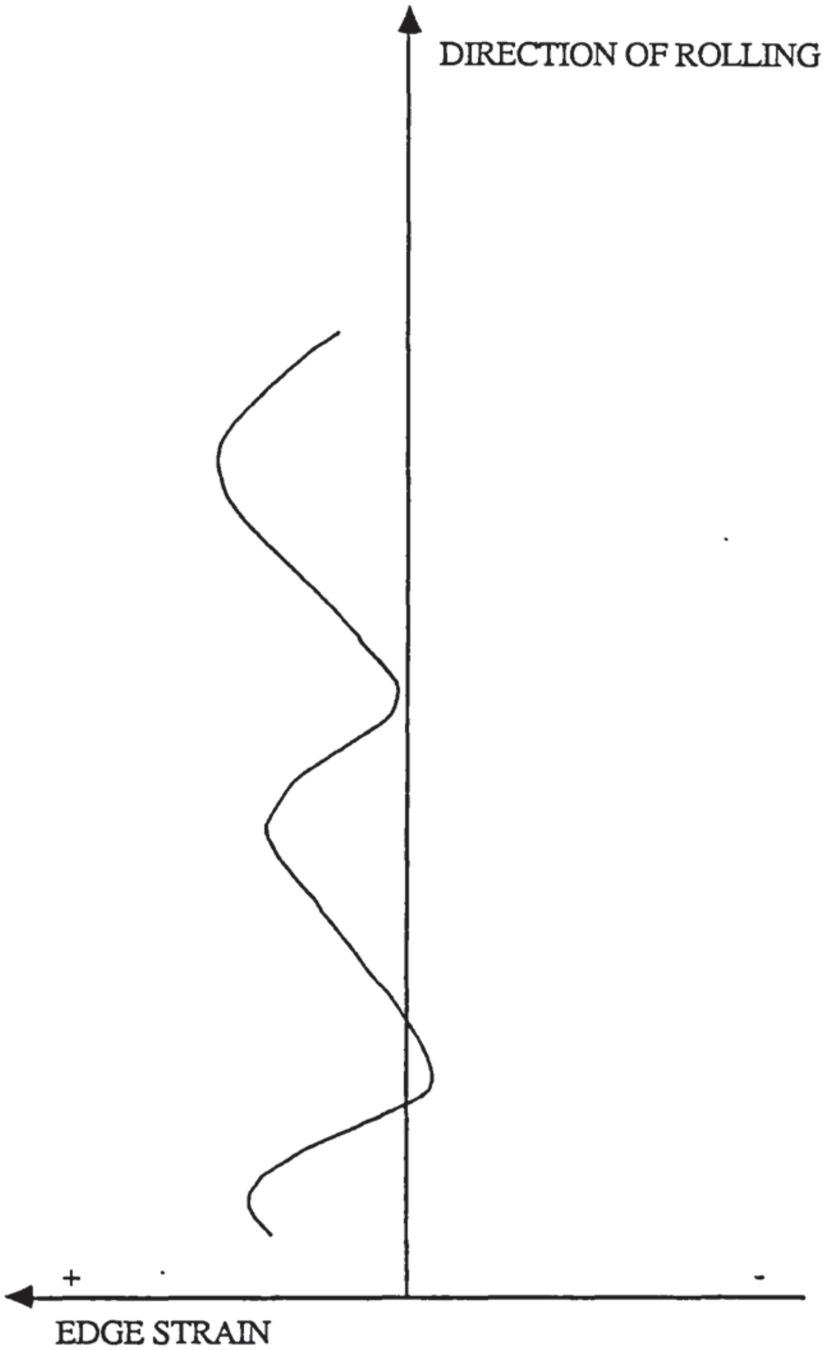


FIGURE 9.18 IDEALISED SHAPE OF EDGE STRAINS

Figure 9.19 Edge strains of deformed specimens, divided into group by thickness

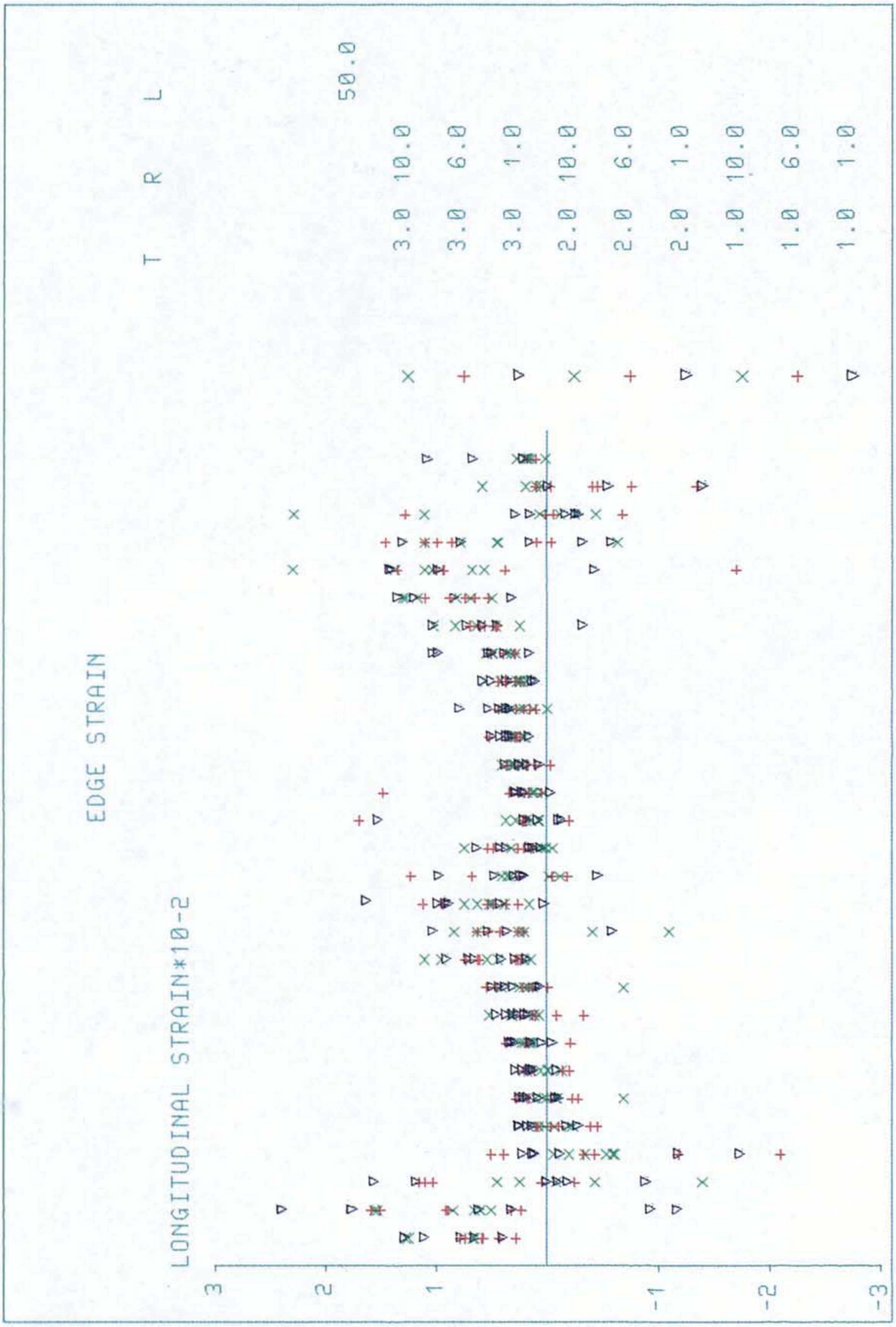


Figure 9.20 Edge strains of deformed specimens, divided into group by inside radius

It is interesting to note that, in this case, as the thickness increases both the maximum edge gradient increases and the edge strain increases. Similarly, there is no apparent relationship, in this case , between radius and either edge gradient or edge strain. The parameter edge gradient, then, would seem to form an easily measured statement of the severity of forming.

Considering Figure 9.17 it can be seen that the "scatter" of the edge strains in the first pass is considerably greater than in the two subsequent passes. The behaviour of the metal as it enters the first set of rolls can be considered as fundamentally different from subsequent passes for the following reason. In the first pass, as the metal moves from flat strip it adopts a shape such as Figure 9.21A, where metal is folding in from the edge and the shape of the metal is extremely difficult to quantify. However, after the first pass the metal tends to fold about the "hinge" formed by the bend (i.e. adopts a shape such as Figure 9.21B).

9.6.3 THE COMPLETE LONGITUDINAL STRAIN FIELD

For three of the deformed specimens the complete longitudinal strain distributions have been obtained for the second and third passes, with the exclusion of exceptional cases where the values have not been collected due to corruption of the scribed grid. Figures 9.22, 9.23 and 9.24 show the strain distrubutions for the sections of thickness 1mm, 2mm and 3mm respectively (where the inside radius is 1mm and the leg length 50mm). With reference to Figures 9.22, 9.23 and 9.24 , the values 1 -19 refer to the values P1 -P19 defined in Table 9.2, the values 2 -25 (running down the page) refer to regions between two successive lines of scribed dots, (where the value 3 is downstream from value 2 and so on) . The values 2-27 are not comparable between the three specimens since it is impossible to stop the mill exactly at any specified point , similarly the interface between pass two and pass three can only be positioned approximately.

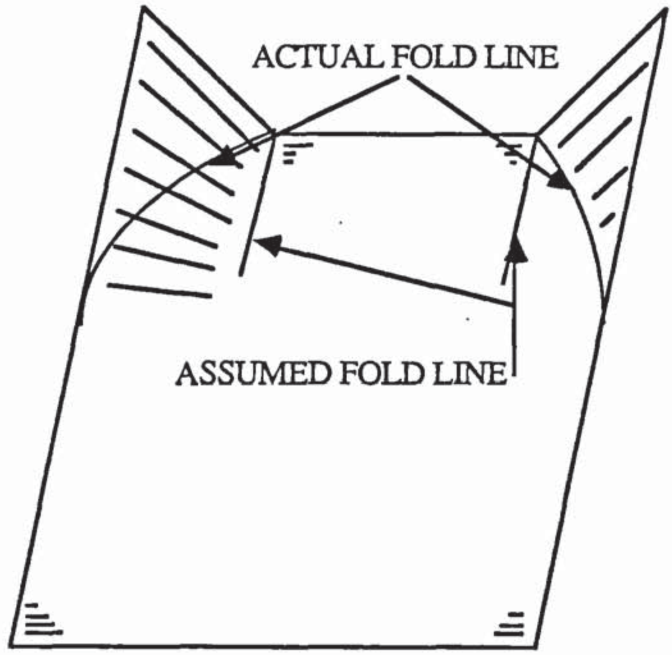


FIGURE 9.21A ASSUMED AND ACTUAL FOLD LINE OF FIRST PASS

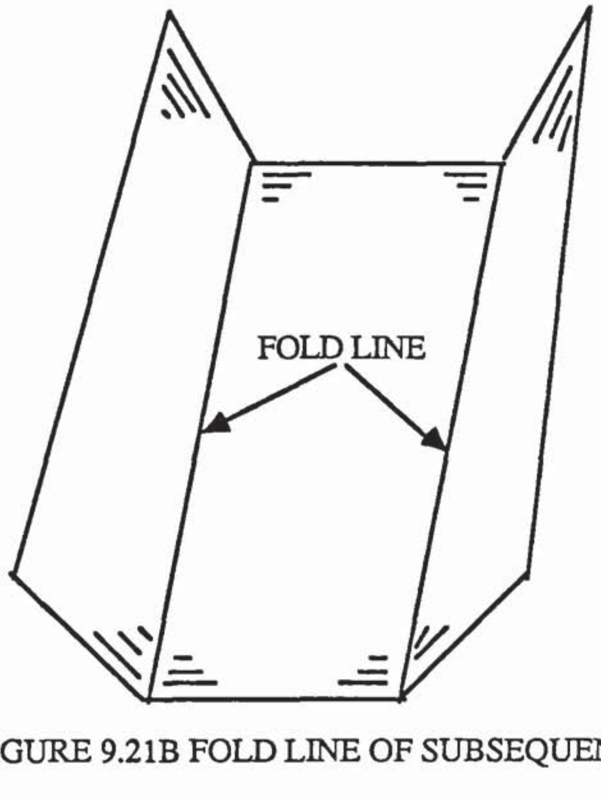


FIGURE 9.21B FOLD LINE OF SUBSEQUENT PASSES

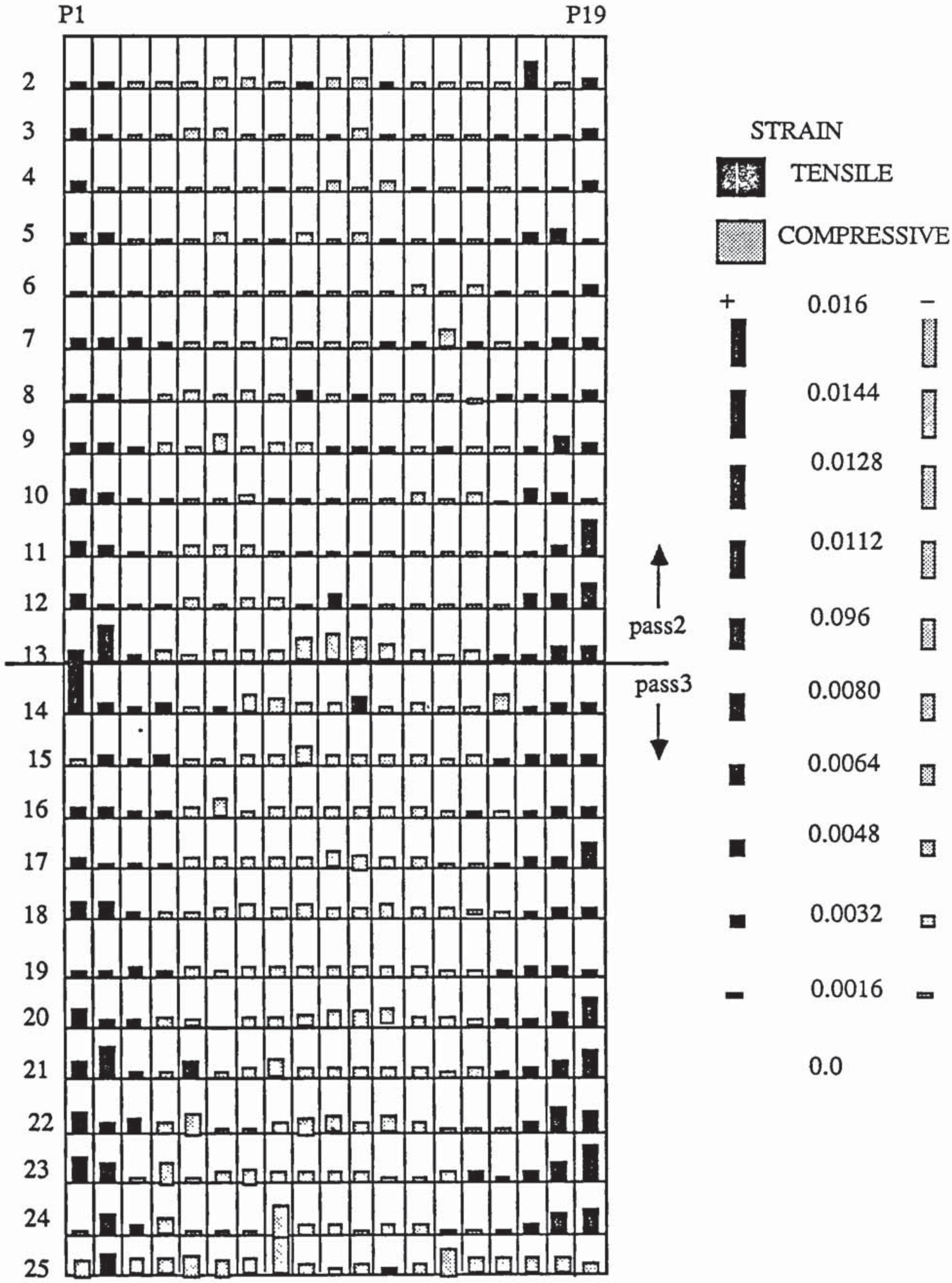


FIGURE 9.22 LONGITUDINAL STRAIN DISTRIBUTION T=1

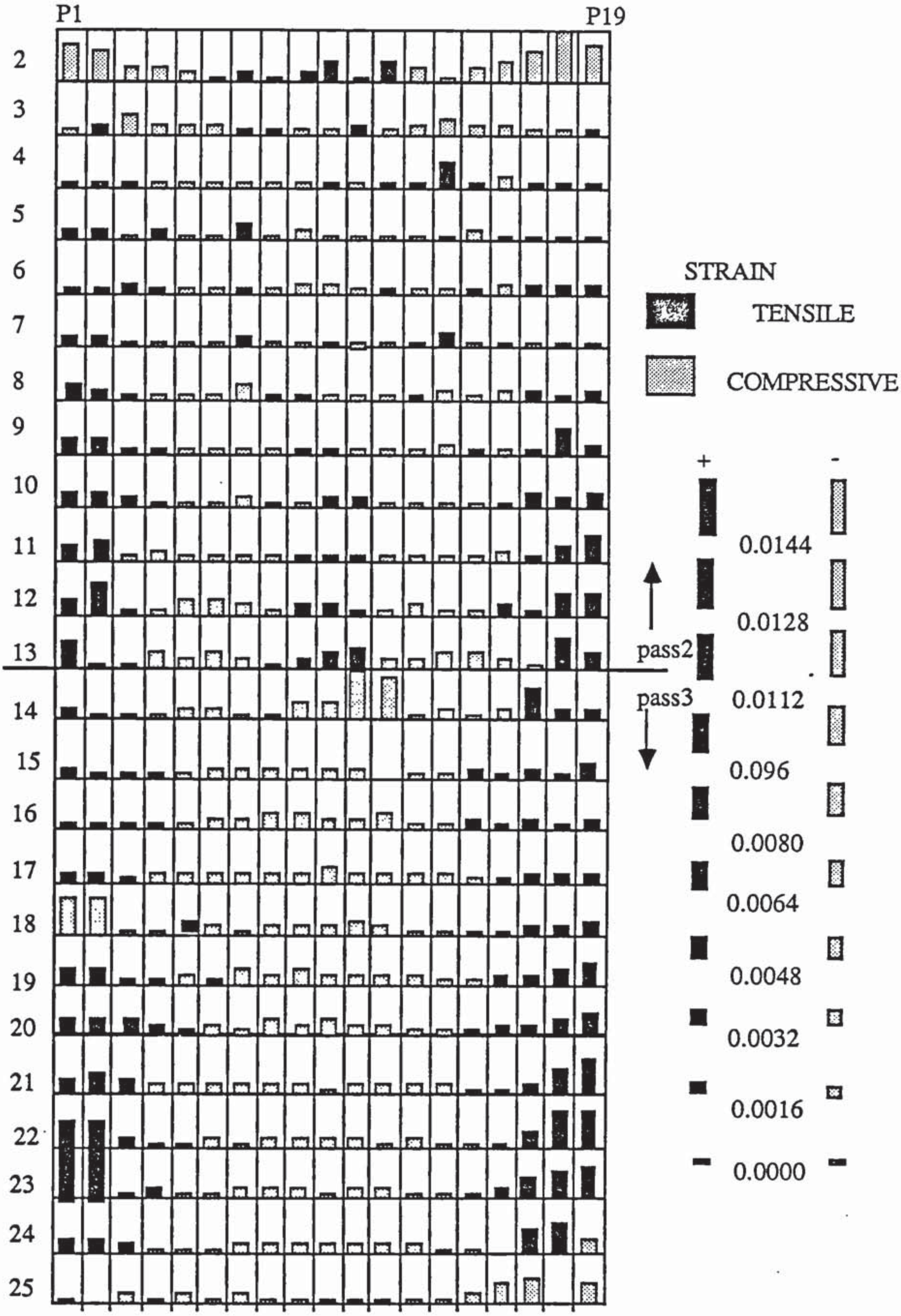


FIGURE 9.23 LONGITUDINAL STRAIN T=2

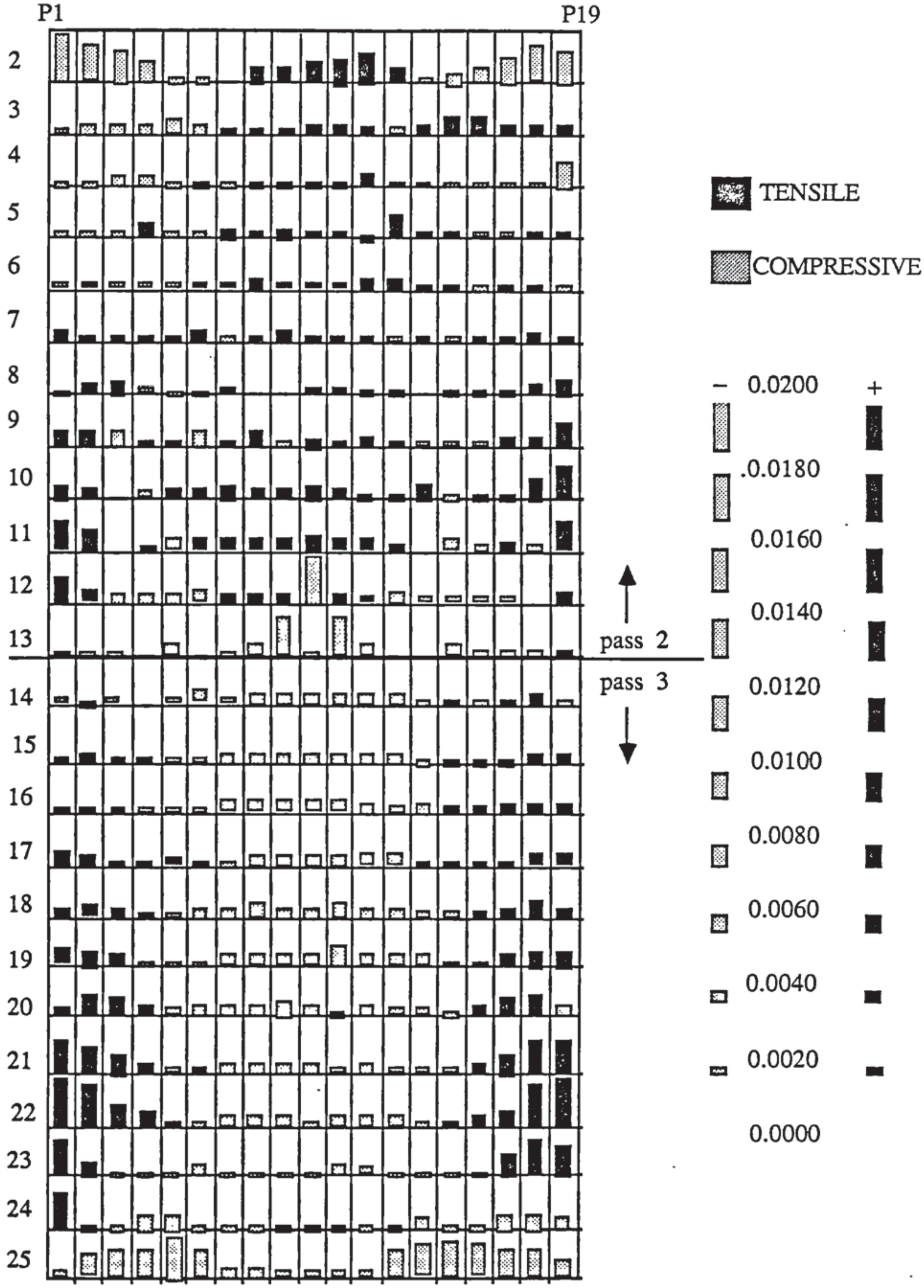


FIGURE 9.24 LONGITUDINAL STRAIN DIISTRIBUTION T=3

Considering Figures 9.22, 9.23 and 9.24 the following observations can be made on the three main regions of the channel; the leg (values P1-P7 and P13-P19), the bend (values P8 and P12) and the base (values P9-P11).

(I) In the leg: the maximum strains occur in all cases towards the upper edge of the channel and the strains decrease towards the base of the leg. This is as would be expected since the metal movement increases towards the top of the leg.

(II) In the bend: towards the base of the leg and in the area of the bend the longitudinal strains tend to become compressive. It would appear that since the radius is small with respect to the thickness the bending can no longer be considered a case of plane strain. Since the neutral axis shifts towards the inner radius the overall strain is compressive.

(III) In the base of the channel the strains are generally compressive, however there are also regions where the strains are clearly tensile.The most clear example of this is seen in Figure 9.24, where the specimen is of thickness 3mm, which shows a definite boundary between the areas of tensile and compressive strains, in the base of the section. An explanation for this effect is as follows; - since pass 3 contains side rolls it cannot be used to drive the metal, since the metal is thick there is considerable resistance to deformation , in order to push the metal through pass 3 the roll pressures have to be increased in pass 1 and pass 2. The high roll pressure in pass 1 means that the metal is being compressed in the thickness direction and hence causing tensile strains in the longitudinal direction. However, when the metal has left pass 2 it is being pushed into pass 3, where it is experiencing considerable resistance to motion and hence compression results.

Another cause of straining in the base of the section is that the base does not always remain flat. Considering Figure 9.25A and Figure 9.25B, a cross section through

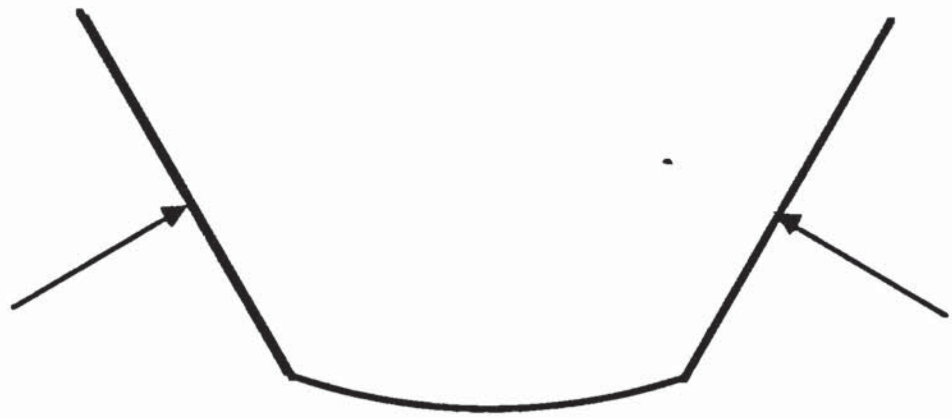


FIGURE 9.25A BASE BENDING AS THE METAL ENTERS THE ROLLS

FIGURE 9.25B THE METAL SHAPE AS IT REACHS THE CENTRE OF THE ROLLS

the metal perpendicular to the direction of rolling as the metal enters the pass would be given by Figure 9.25A, where the upward bending of the legs causes the base to adopt a curved profile. However , as the section moves through the pass the rolls flatten the linear element (as in Figure 9.25B). This process of 'bending and flattening' results in the relatively high compressive strains apparent in the base of the section. These strains are particularly noticeable in the second pass.

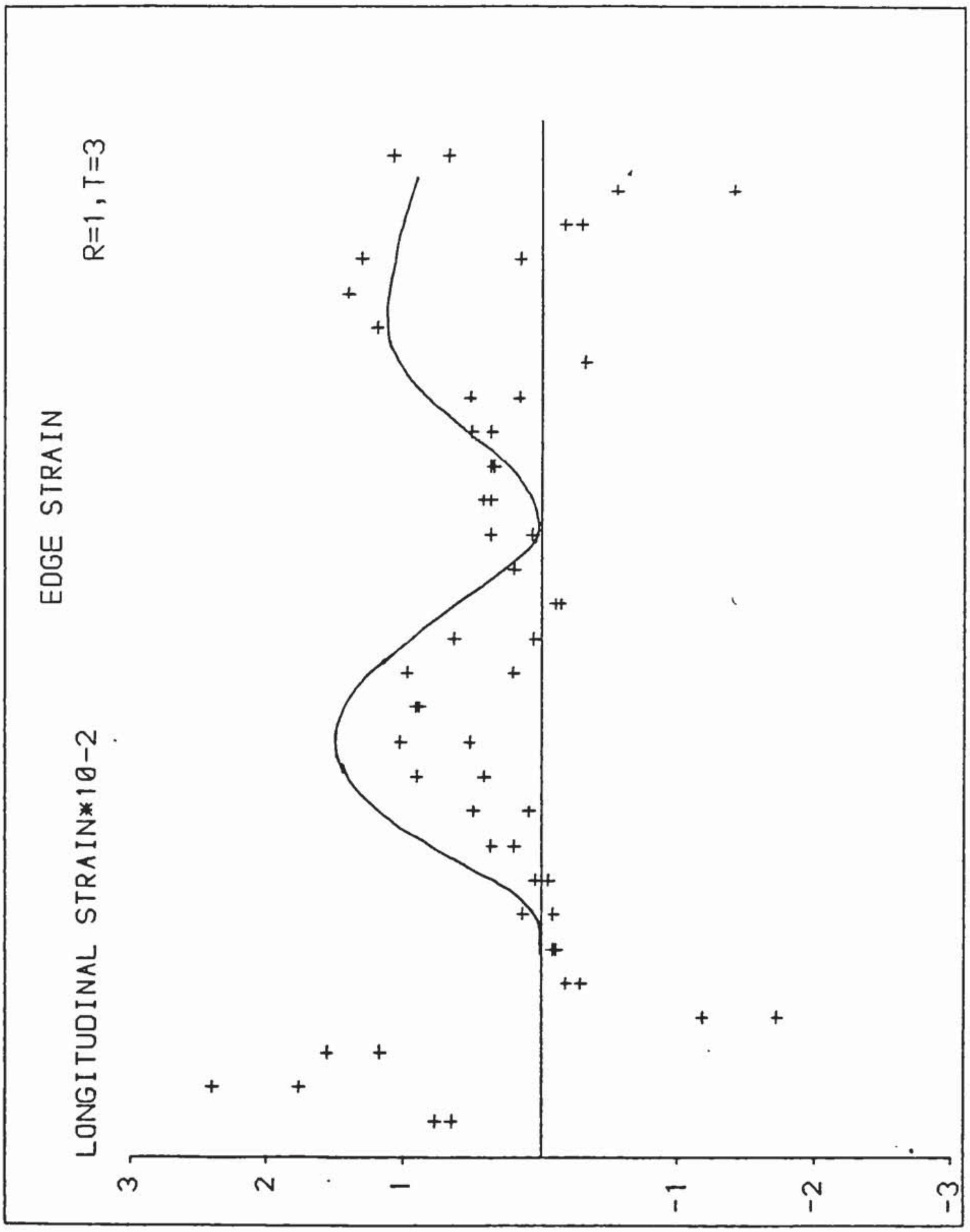
9.7 INDIVIDUAL EDGE STRAIN DISTRIBUTION OF THE DEFORMED SPECIMENS

This section will consider the edge strains of some of the deformed specimens individually and compare the experimental results with those obtained theoretically from the numerical analysis detailed in chapter 7. Figures 9.26 - 9.31 show the edge strains of the deformed specimens; R=1, T=3; R=6, T=3; R=10, T=3; R=1, T=2; R=6, T=2; R=10, T=2 respectively; plotted on the same figures as smooth curves drawn through the theoretically generated data.

The theoretical results were obtained using the following conditions. The pass length of the mill was 240.0 mm , the flower pattern and the finished sections were those previously defined in sections 9.2 and 9.4 respectively , the pass height and roll centre to centre distances were those previously defined in section 9.4 . Each element was devided into 6,10,6 "brick" elements in the transverse, longitudinal and thickness directions respectively. The rigid plastic option was used throughout . From considering Figures 9.26 - 9.31 the following points can be noted.

(1) The theoretical values for the maximum edge strains of the deformed specimens are of the same order of magnitude as the experimental data.

(2) The shape of the distribution of theoretical values approximates that of the distribution of experimental values. The "noisiness" of the experimental data



+ EXPERIMENTAL

— THEORETICAL

FIGURE 9.26 INDIVIDUAL EDGE STRAINS T=3 R=1

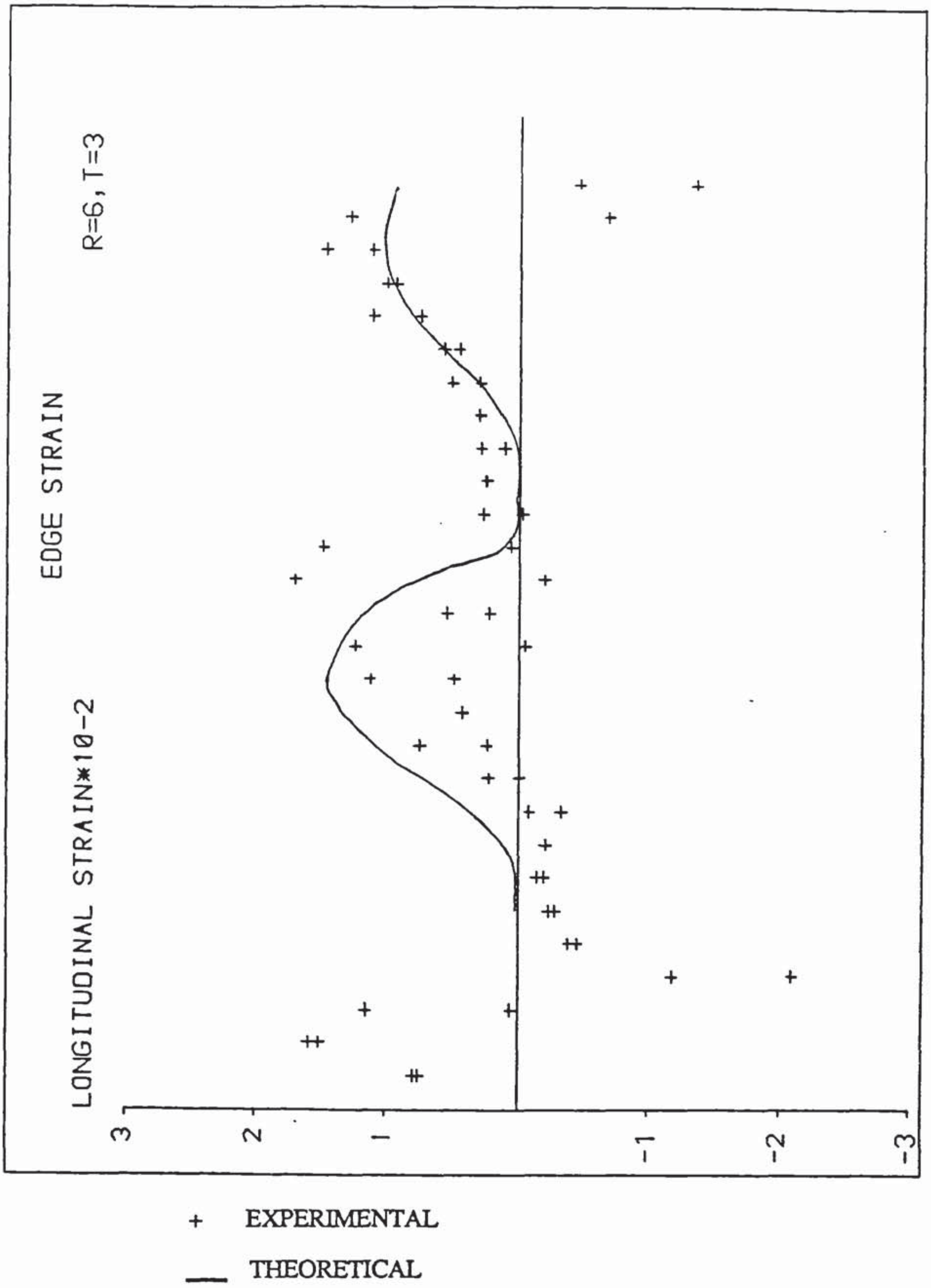
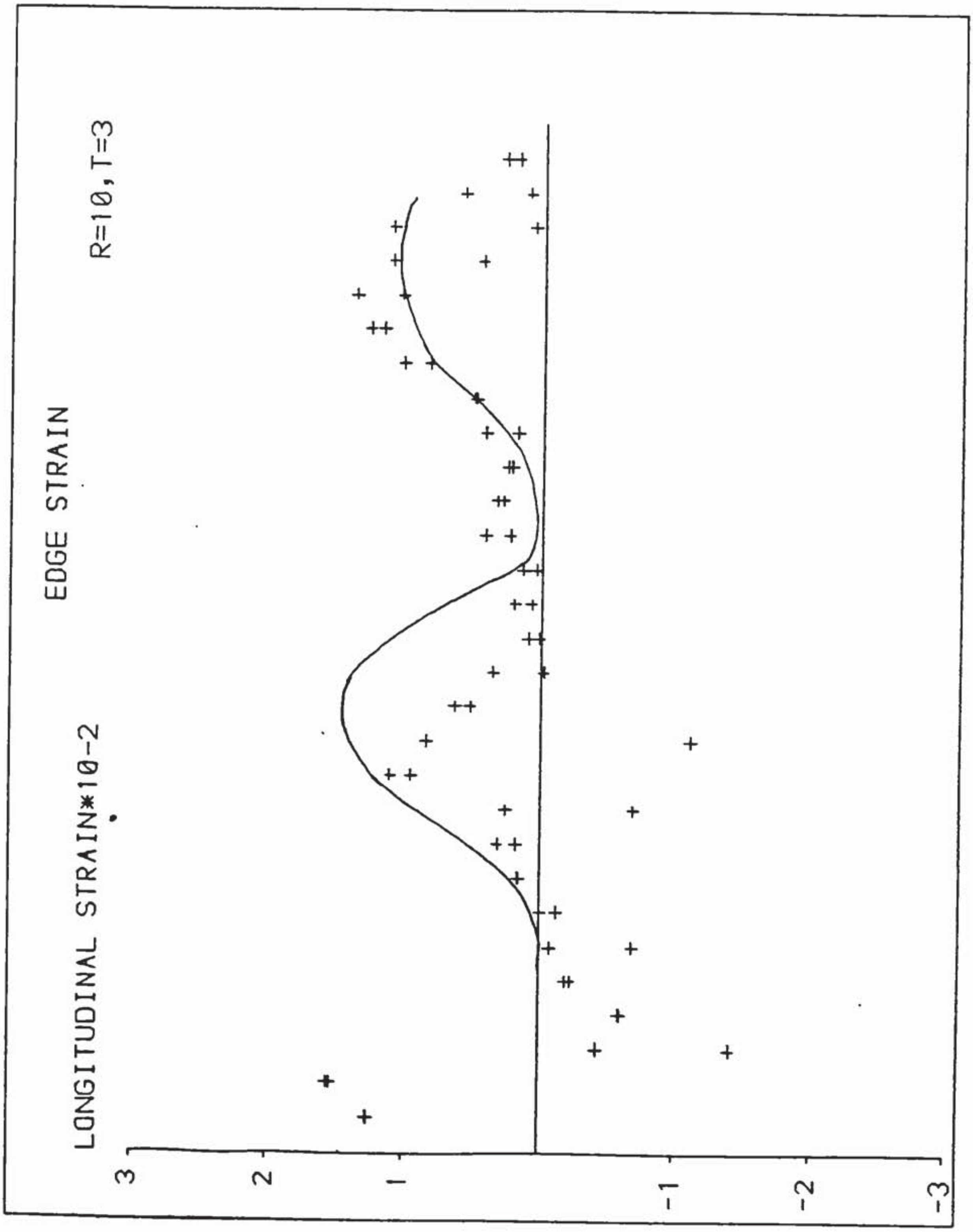


FIGURE 9.27 INDIVIDUAL EDGE STRAINS T=3 R=6



\+ EXPERIMENTAL

— THEORETICAL

FIGURE 9.28 INDIVIDUAL EDGE STRAINS T=3 R=10

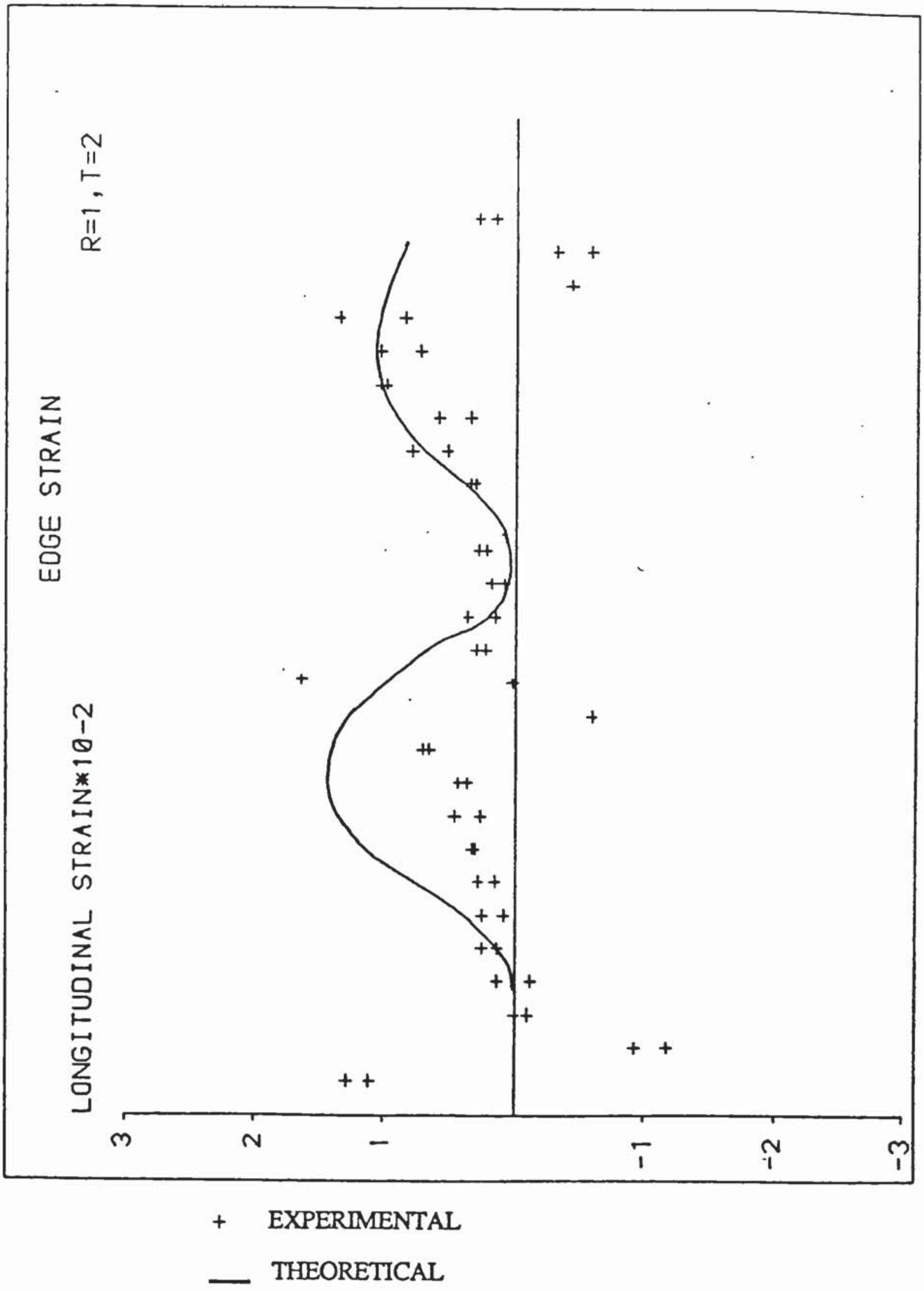
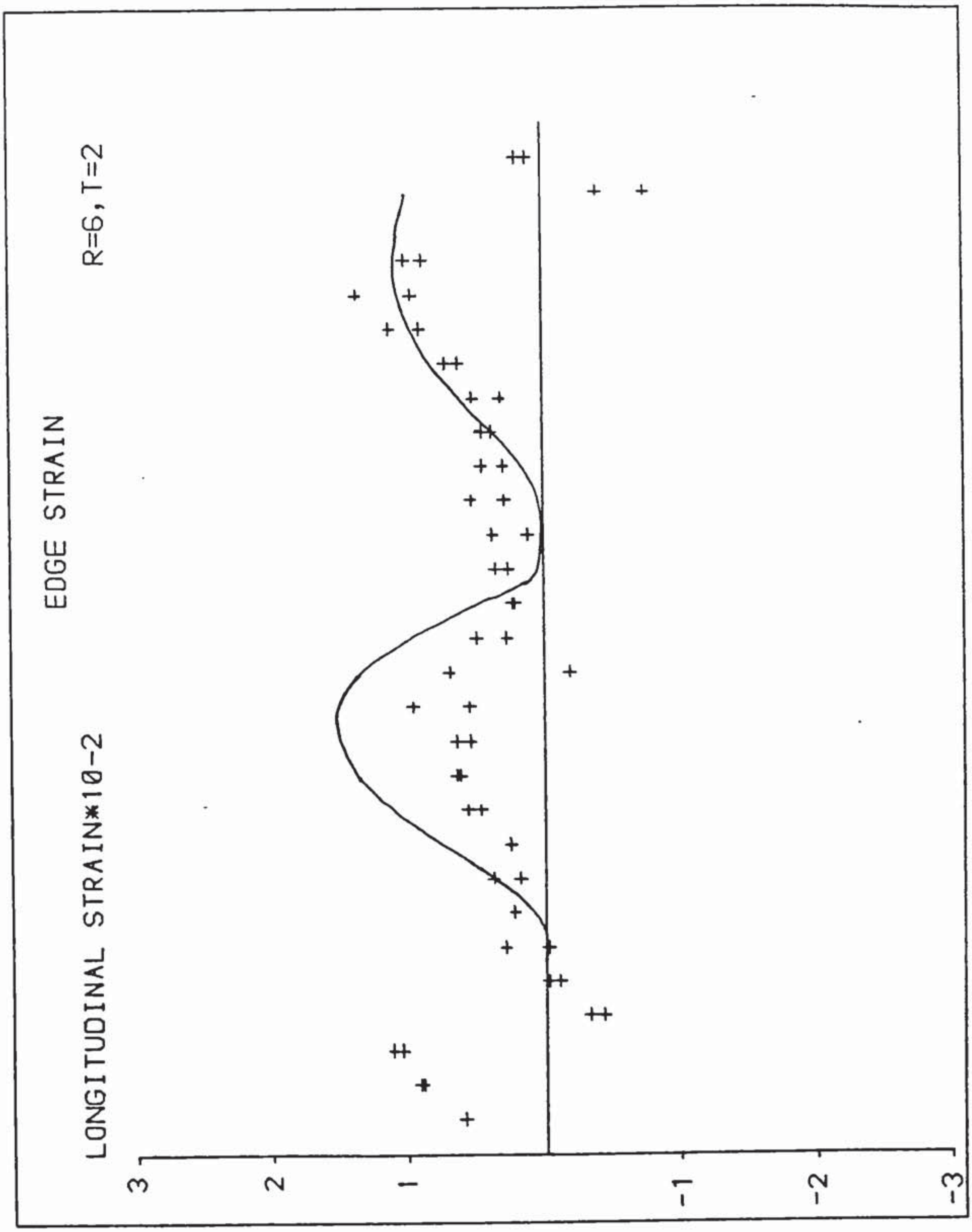


FIGURE 9.29 INDIVIDUAL EDGE STRAINS T=2 R=1



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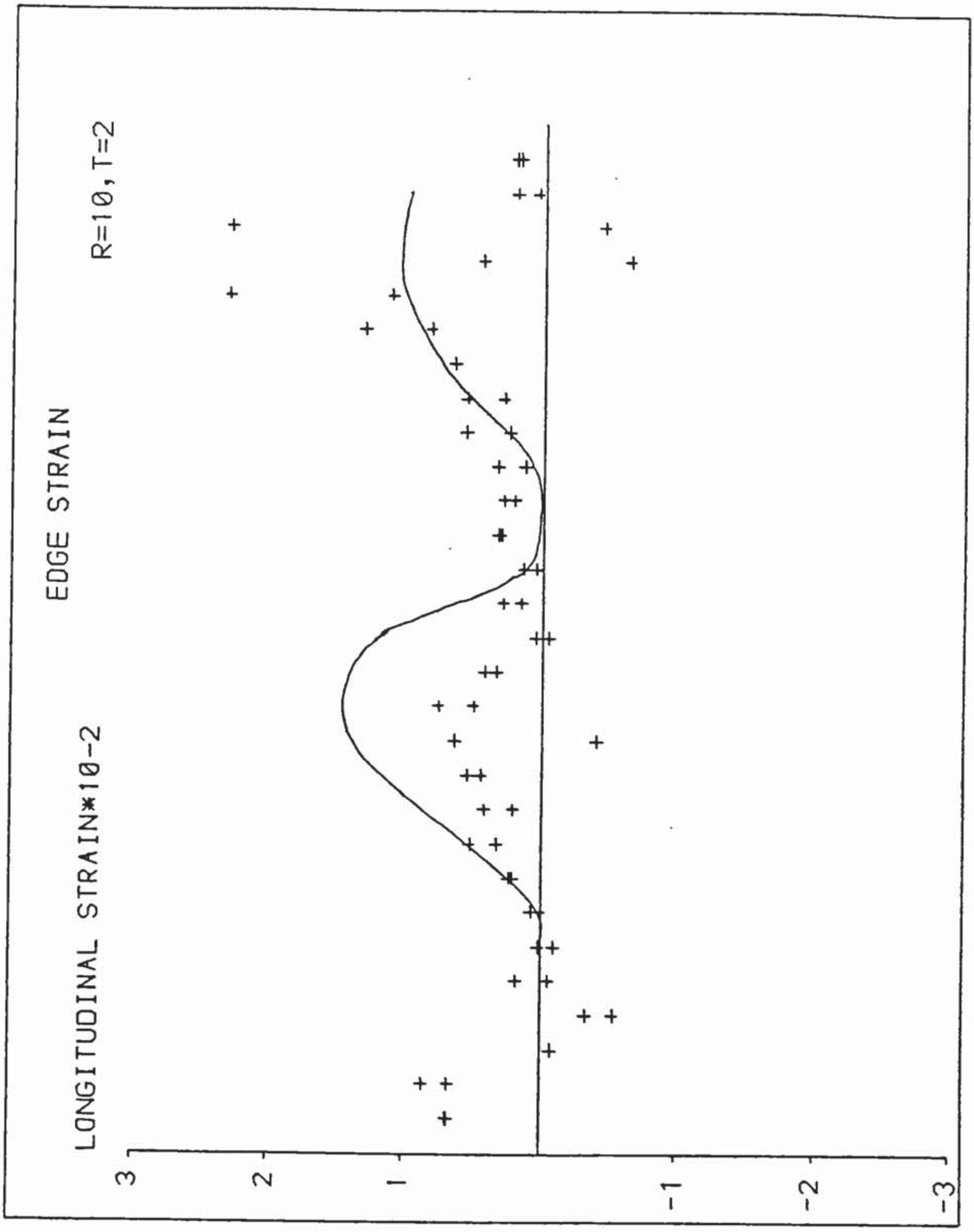
— THEORETICAL

FIGURE 9.30 INDIVIDUAL EDGE STRAINS T=2 R=6



+ EXPERIMENTAL

—— THEORETICAL

FIGURE 9.31 INDIVIDUAL EDGE STRAINS T=2 R=10

precludes any more detailed comparison.

(3) The theoretical values have not been supplied for the first pass since, as was mentioned in the previous section, the deformation during the first pass is fundamentally different from successive passes. In practice, this means that the level of longitudinal strain reached during the first pass is significantly larger than would be expected from the theoretical values.

(4) For the second pass, in general, the theoretical edge strain values are larger than the experimental values. This is as would be expected since, the experimental values obtained from the deformed specimens are smaller than the true values due to springback.

(5) For the third pass, in general, the theoretical edge strain values are of similar magnitude to, or, on occasion, slightly smaller than the experimental values for edge strain. Comparing the second and third passes, the experimental values can be seen to be greater in the third pass than in the second pass, whilst the theoretical values can be seen to be greater in the second pass than the third pass. It would be expected that the edge strain would be larger in the second pass since, the metal movement is larger. Hence, there must be an additional source of deformation other than those detailed in chapter 7.

It was noted earlier, in section 9.6, that the use of side rolls had a significant effect on the longitudinal strain distribution in the base of the section. In particular, it was noted that whether a pass was driven or was not driven was influential on the final strain distribution. It would appear, then, that combined with the compressive strains in the base of the section ,when using side rolls, is an increase in the tensile longitudinal strain at the edge of the leg.

To conclude, the comparison of the theoretical and experimental values for individual specimens has shown the model described in chapter 7 to possess considerable promise. By considering the experimental data presented in this chapter, three additional forms of deformation have been isolated, which should , if possible, be included in any future model attempting to realistically approximate the strain distribtion . These are, deformation caused , in the base, by the roll pressure, deformation occuring when a pass is not being driven (but is being pushed into the rolls by precedeing passes) and deformation caused by the base bending.

CHAPTER 10

CONCLUSIONS AND FUTURE WORK

10.1 CONCLUSIONS

In the introduction it was noted that the development of the computer aided design software could be considered in three phases. Namely: - the computerisation of existing standards and practices within the collaborative organisation, the application of existing knowledge which had not previously been employed by the collaborative organisation and the development and application of new techniques for aiding the design of form rolls. In general, it can be said that the first two phases have been largely completed and that, whilst the third phase can never be totally completed, a contribution has been made in the form of new techniques and methods of analysis. The specific conclusions of the research are that :-

(1) It has been shown that the CAD/CAM system can be successfully installed as a multi user system. The system is presently implemented on a micro VAX II computer for five users. However, the system has been designed so that the potential number of users is open ended. To ensure additional users can rapidly become accustomed to the system, the individual programs can all be accessed through a single command via a menu structure. Parallel to the CAD/CAM system a menu driven help system has been developed so that as new users are introduced to the system they can guide themselves through the programs.

(2) The existing methods for generating the strip length have been examined and the necessity for a new algorithm found. As the lead time for producing form rolls decreases it becomes more important to order the correct strip width first time, often the lead time for ordering material is greater than the lead time for producing form rolls. The new algorithm developed considers the material type, the inside radius,

the material thickness and the angle of bending; previously at most only two of these parameters were considered. An open ended system has been chosen which allows the designer to define the material groups, which he considers fundamentally different, and to define the bend factors (which control strip length) from his own experience. By comparing actual and theoretical strip lengths the designer can continually update the information defining strip length and hence work towards the ideal strip length.

(3) The techniques for estimating springback have been examined and two new methods have been developed to aid the designer in understanding and alleviating springback. Firstly, the springback estimation program gives the designer a pictorial and numeric representation of the general tendency of a particular curve to springback. Secondly, a new method for forming bends has been developed which provides significant advantages over the two common methods of forming the bend (the constant inside radius method and the constant element length method).

The automatic composite element length method takes as its premise the assumption that springback only becomes important above a certain, user defined, maximum permissible value. The radius is then maximised until either the maximum permissible springback level is reached or the radius for constant element length is reached.

(4) A new method for estimating springback has been developed, based on the assumption that the metal will springback to the shape that will minimise the elastic energy stored in the metal. It can be proved that, when the assumptions made in deriving Gardiners equation (the classical method of estimating springback) are made, the expression derived by considering minimum elastic energy is identical to Gardiners equation.

(5) A new limited input flower pattern design program has been developed, based on a study of the practice of flower pattern design and the existing theory of flower pattern design, which partially generates flower patterns. The program has been structured to reflect more closely the conventional procedures of flower pattern design and consists of three sections. Firstly, the designer inputs those passes which he considers compulsory to the successful rolling of the section. Secondly, the program generates intermediate passes for forming between the compulsory passes. The number of intermediate passes is determined by considering the sideways metal movement, the power requirements and the springback. Thirdly, the program generates the optimal means of forming the bend using the automatic composite element length method detailed in conclusion (3). To fulfil the stated philosophy of maximum flexibility with minimum input it is necessary to provide the designer with comprehensive editing facilities. Employing these facilities , the user has the facility to alter the design after the second or third stages to his own requirements.

(6) From a study of cold roll forming, with particular emphasis on the theoretical and experimental analysis of form roll design, the following points can be noted:-

(I) The commercial importance of cold roll forming has not been reflected in the amount of research conducted into the process. This, is probably a reflection of the complexity of the cold roll forming process.

(II) Experimental research into cold roll forming can be generalised into three areas, fundamental research, research into "optimum" roll design and research into problems occuring in the rolling of specific sections. Of the three areas the majority of research falls into the third category.

(III) There appears to have been little theoretical analysis of the cold roll forming process. Of those attempts which have been made, the most popular approach is to use a minimum energy method.

(7) A method for the construction of a model for numerical analysis of the cold roll forming process has been detailed. The model is based on a minimum energy method and it is believed that it represents the first attempt to numerically analyse the form rolling process for any general section. A new method for the geometric definition of the shape of metal between successive passes in the cold roll forming process has been devised based on an experimental study of the distribution of bending between passes. The model varies the shape of the metal between passes and takes the metal shape which minimises power as representing the actual shape. By modelling the cold roll forming process it is hoped to provide the data which will allow the form roll design to be stated satifactory or unsatisfactory at the design stage.

(8) A procedure for obtaining experimental results has been developed. Firstly, a regular grid of scribed dots is machined onto the material surface. Secondly the material is fed into the mill and the mill stopped when the scribed section of the strip is between the beginning of the first pass and the end of the final pass. Thirdly, the top rolls are removed and the defined strip lifted out. Finally, the three dimensional coordinates of the scribed points are obtained and the strain measured.

(9) Using the experimental procedure described in the previous section deformed strips were obtained for twenty seven channel sections, varying inside radius, thickness and leg length. From these deformed strips the following results were obtained.

(I) As the thickness increases the severity of forming, measured by either longitudinal strain or edge gradient increases.

(II) As the leg length increases the severity of forming, measured by edge gradient increases. However, the severity of forming is not directly related to leg length, since, the bending becomes more evenly distributed as the leg length increases.

(III) No relationship was observed between the inside radius and severity of forming.

(IV) The channel could be considered as consisting of three regions :- the leg, the bend and the base. In the leg the longitudinal strains are generally tensile, the strains are largest at the top of the leg and decrease towards the base. In the bend and towards the base of the leg the strains tend to become compressive. In the base of the section the strains can be either tensile or compressive, where the roll pressure and the use of side rolls seem to be particularly influential.

(10) New techniques have been found necessary to give the designer an enhanced visualisation of the effects of form roll design. From practical observation and industrial feedback the importance of visual techniques in improving form roll design has been confirmed. The following "views" of the form rolling process have been found to be particularly important.

(I) The plan view, is an attempt to show the shape of the metal as it passes through the rolls, as it appears from looking down onto the mill.

(II) The side view, is an attempt to show the shape of the metal as it passes through the rolls as it appears looking from the side of the mill.

(III) The wire frame view, is a pseudo three-dimensional representation of the shape of the metal as it passes through the mill. It is obtained by plotting the template shape at each pass and joining successive templates by straight lines.

(IV) The metal shape view, is an attempt to represent the true three-dimensional shape of the metal as it passes through the rolls. It is obtained by plotting the template shape at each pass, and then generates intermediate template shape utilising the results of the numerical analysis.

(V) The single pass view is an attempt to represent the true three-dimensional shape of a single pass of the form rolling process. As such, it provides the ideal framework for outputting the results of the numerical analysis.

10.2 FUTURE WORK

Prior to introducing the suggestions for future work it will be illuminating to reconsider the main text and to review the present state of computer aided design of form rolls. The CAD/CAM system, described in this thesis, provides a comprehensive range of facilities for the design and manufacture of form rolls. The principal limitation of the CAD/CAM system remains the need to manufacture rolls and test them on the mill before the design can be stated satisfactory or unsatisfactory. However, as a device for producing the form rolls quickly and accurately the system can be considered largely effective.

In general there are two complementary methods to alleviate the need to manufacture rolls prior to assessing the designs suitability. Firsly, numeric analysis of the form rolling process and secondly flower pattern generation. Presently the limiting constraint, particularly in the second method, is knowledge of the cold roll forming process. Thus, whilst this thesis's approach has been to research into methods by which the computer can aid form roll design, a prerequisite to future research into the computer aided design of form rolls is further research into the process of cold roll forming. Specifically it is suggested that the following areas would repay future investigation.

(I) With reference to Figure 6.1, a major constraint on experimental analysis of cold roll forming is the lack of any accepted general definition of section quality. Quality is inevitably a combination of a large number of individual elements, in cold roll forming the components which collectively form quality have still to be isolated and defined. This means that, in general, whilst there are British Standards relating to sectional quality, the quality of cold roll formed sections is still to a large extent assessed subjectively. Hence, a limitation on experimental work is that, when varying any parameter of the cold roll forming process it is difficult to observe the effect on the components of quality. Valuable future work, then, could be performed defining the quality of cold roll formed sections. The following areas would be particularly rewarding.

(I) Isolating and defining the ways in which a section can be considered unsatisfactory.

(II) Developing methods for quantifying section defects.

(III) Developing a standard terminology for section defects.

Such work would be of value to cold rolled section manufacturers, cold rolled section users and those performing experimental analysis of cold roll forming.

(2) Whilst isolating and defining the section defects a parallel investigation would be to identify the mechanisms by which these defects occur and to study the relationship between strain distribution and defect occurance.

Many, geometric, defects can be considered as the sections tendency to dissipate elastic energy. An expression for springback has been derived by assuming the metal will take the shape which minimises the elastic energy stored in the metal. A potentially extremely rewarding area of future work would be to investigate the derivation of expressions for other section defects, such as curvature, using this method.

(3) The conventional wisdom is that it is the magnitude of longitudinal straining which is the primary influence on the occurance of section defects. However, the setter can obtain "straighter" sections by using methods which clearly put additional straining into the metal (such as increasing roll pressure or moving the section out of line). This leads to the conclusion that it is not purely the magnitude but the magnitude and distribution of longitudinal straining which determines the occurance of many section defects. With regards to this fact potential areas of future work are:-

(I) To attempt to quantify the magnitude and distribution of additional straining required to produce the "straightest" section.

(II) To investigate the most suitable method of introducing additional straining into the material to produce the straightest section. It would be particularly interesting to investigate the possibility of producing a better quality section by introducing selective pre-straining into the material whilst it is still flat.

(4) With reference to Figure 6.1, it can be seen that the parameters which are known to define the cold roll forming process, and which collectively determine the section quality, can be generalised into three groups. Namely, operating conditions, material properties and tool design. However, within these three groups, the definitive list of parameters which determine sectional quality has yet to be compiled. This is one of the major limiting factors on the numerical analysis of form roll design and the generation of form roll design. Future work is required in obtaining a more detailed understanding of the factors which define the form rolling process, their interrelationship and their influence on quality.

(5) Numerical analysis of the form rolling process is an extremely complex area, however, it is an area which is potentially extremely rewarding. It is suggested that to improve the existing work two main areas should be examined. Firstly, a long term objective would be made to determine the full range of parameters which affect the strain distribution. Secondly : in order to maintain the computing time to a reasonable level the number of parameters used to construct the strain field are necessarily kept to a minimum. However, this restricts the range of potential strain distributions. A major research area requiring further investigation is to compare experimentally obtained strain distributions with modelled strain distributions and to formulate new methods of constructing strain fields.

(6) When generating flower patterns or performing numeric analysis of form roll design there is an argument that the range of sections which can be produced by cold roll forming is so large that one cannot formulate methods for the general case. This leads to the conclusion that the range of sections should be divided into a number of sub-groups. Rather than form these groups arbitarily there is a case for developing a coding system for cold roll formed sections and hence by cluster analysis techniques categorise these sections into groups with similar characteristics. Developing a coding system for cold roll formed sections would have the following additional advantages. Firstly, in general ,rolling mills can be considered to be of two main types, either they are designed to form a particular section or they are designed to form any section (or any section within a wide range). By analysing the sections a company rolls it would be possible to form groups of sections requiring a similar type of rolling mill, hence it would be possible to advise on the appropriate designs of rolling mill and auxiliary equipment which should be owned by the company. Secondly, it is often useful for a designer to examine past designs of a similar nature when quoting for a job or designing a set of rolls, using the coding system a database of past designs could be collected on the computer and all designs of a similar nature could be retrieved as required.

APPENDIX A

EXAMPLE SESSION OF ROLFORM CAD/CAM SYSTEM

IN THIS APPENDIX A SAMPLE SESSION, TO PRODUCE SECTION 1861, IS CONTAINED TOGETHER WITH ALL OF THE DATA FILES AND AN EXAMPLE OF AN N.C LISTING

```
      ROLFORM  METAL DIRECTORY
      ------------------------


          METAL                            KEYWORD
          -----                            -------

   (1)    STEEL                            STEEL
   (2)    HIGH STRENGTH STEELS             HIGH
   (3)    STAINLESS STEELS                 STAINLESS
   (4)    NON FERROUS METALS               NONFE

      PLEASE TYPE KEYWORD
                  =======
 METAL:STEEL
```

```
     ROLFORM CAD/CAM SYSTEM
     ======================

     PROGRAM                                 KEYWORD
     =======                                 =======

(1)   INPUT SECTION DATA                     SECTION
(2)   RERUN SECTION ON SCREEN                NSECTION
(3)   RERUN SECTION ON PLOTTER               MSECTION
(4)   INPUT FLOWER PATTERN DATA              FLOWER
(5)   RERUN FLOWER PATTERN ON SCREEN         NFLOWER
(5A)  RERUN FLOWER PATTERN SEPERATELY        SFLOWER
(6)   RERUN FLOWER PATTERN ON PLOTTER        MFLOWER
(7)   RUN TEMPLATE PROGRAM                   TEMPLATE
(8)   RUN TEMPLATE ON PLOTTER                MTEMPLATE
(9)   INPUT ROLL DESIGN DATA                 DESIGN
(9A)  INPUT ROLL D-DATA IN SINGLE STAGE      SDESIGN
(10)  RERUN ROLL DESIGN ON SCREEN            NDESIGN
(11)  RERUN ROLL DESIGN ON PLOTTER           MDESIGN
(12)  RUN WIRE FRAME ON SCREEN               WIRE
(13)  RUN WIRE FRAME ON PLOTTER              MWIRE
(14)  RUN PLAN/SIDE ON SCREEN                VIEW
(15)  RUN PLAN/SIDE ON PLOTTER               MVIEW
(16)   EDIT ROLL DESIGN                      AEDITOR
(17)   INPUT CUTTING COMMANDS                CUTPLOT
(18)   RERUN CUTPLOT ON SCREEN               NCUTPLOT
(19)   RERUN CUTPLOT ON PLOTTER              MCUTPLOT
(20)   RUN POST PROCESSOR                    MFPOST
(21)   CHECK NC TAPE ON SCREEN               CHK
(22)   CHECK NC TAPE ON PLOTTER              MCHK

       TYPE 99 TO EXIT                      (KEYWORD)

     PLEASE TYPE KEYWORD TO SELECT A PROGRAM
                 =======
 CHOICE:SECTION



       NSECTION       VERSION 1.1
```

```
                    *** ROLFOM ***
                        ******

            ** FINISHED SECTION PROGRAM **


*** PLEASE INPUT THE SECTION NO. ***
section no. = ?
1861
  ****************************************
  **                                    **
  **         TERMINAL DEFINITION        **
  **         PLEASE INPUT  1,2,3,4      **
  **         (1) FOR T4010              **
  **         (2) FOR T4107              **
  **         (3) FOR T4113              **
  **         (4) FOR VT125              **
  **                                    **
  ****************************************
2


           * PLOTTING PROGRAM NO. 1 FOR ROLLED-SECTION *

                            FINISHED SECTION
                            ----------------



  PLEASE SUPPLY THE FOLLOWING DATA ACCORDING TO THE GIVEN
FORMAT:-

INPUT UNIT         OUTPUT UNIT        THICKNESS          ORIGIN
----------         -----------        ---------          ------
  (INTEGER)          (INTEGER)          (REAL)         (INTEGER)
```

```
WHERE,

   INPUT UNIT IS IN INCH(1) OR MM(2),
   OUTPUT UNIT IS ALSO IN INCH(1) OR MM(2),
   THICKNESS IS THICKNESS OF STRIP,
   ORIGIN IS THE STARTING POINT FOR ELEMENT DEFINITION
SEQUENCE LATER ON.

   ORIGIN=1 IF FROM LEFT TOWARDS RIGHT (ONE-SIDED).
   ORIGIN=2 IF FROM RIGHT TOWARDS LEFT (ONE-SIDED).
   ORIGIN=3 IF FROM CENTRE TOWARDS RIGHT AND THEN FROM CENTRE
TOWARDS LEFT.
   ORIGIN=4 IF FROM CENTRE TOWARDS LEFT AND THEN FROM CENTRE
TOWARDS RIGHT.
   ORIGIN=5 IF FROM CENTRE TOWARDS RIGHT (SYMMETRICAL
SECTION).


 ** PLEASE INPUT IUNIT,OUNIT,THICK,ORIGIN **
2     2      5.0000       4



   PLEASE ENTER THE DATA FOR ELEMENT DEFINITION SEQUENCE
ACCORDING TO THE GIVEN FORMAT,
   ONE DEFINITION STATEMENT FOR EVERY ELEMENT ENTERED :-


SEQUENCE         ELEMENT          LENGTH OR        ANGLE OF
NUMBER (N)       TYPE (TYPE)      RADIUS           BENDING
-----------      -----------      -----------      -----------

(INTEGER)        (INTEGER)        (REAL)           (REAL)


START FROM 1,    1 = LINEAR,      POSITIVE         FOR TYPE 2
INCREMENT        2 = CIRCULAR,    LENGTH           ELEMENTS
BY 1             THE REST ARE     FOR TYPE 1,      ONLY,
UP TO 50,        ILLEGAL.         INSIDE RADIUS    ZERO FOR
                                  FOR TYPE2        TYPE 1,

   *THE EXCEPTION BEING, WHEN N=1 AND TYPE=1 (AND ORIGIN NOT
5!),
    ANGLE OF BENDING IS TAKEN AS THE ANGLE OF INCLINATION
    BETWEEN THE HORIZONTAL-AXIS AND THE FIRST LINEAR ELEMENT,
    PERMISSIBLE RANGE IS FROM -90 TO +90 DEGREES.
```

NOTE THAT WHEN ORIGIN IS 3 OR 4 (DOUBLE SIDED DEFINITION), 2 SETS OF DEFINITION SEQUENCE ARE REQUIRED,
ONLY 1 SET IS REQUIRED WHEN ORIGIN IS 1,2 OR 5.
FIRST ELEMENT AND LAST ELEMENT OF THE SEQUENCE MUST BE LINEAR.
MAXIMUM NO. OF ELEMENTS IN EACH SEQUENCE MUST BE LESS THAN 50.

1	1	7.00 MM.	0.00
2	2	2.50 MM.	90.00
3	1	8.00 MM.	0.00
4	2	2.50 MM.	-90.00
5	1	32.50 MM.	0.00
0	0	0.00 MM.	0.00
1	1	7.00 MM.	0.00
2	2	2.50 MM.	90.00
3	1	25.50 MM.	0.00
0	0	0.00 MM.	0.00

MEANLENGTH INFORMATION FOR INDIVIDUAL ELEMENTS:-

ELEMENT NO.	MEANLENGTH (MM.)
1	7.000
2	7.069
3	8.000
4	7.069
5	32.500
6	7.000
7	7.069
8	25.500

TOTAL MEANLENGTH= 101.206 MM.

PLEASE SELECT THE PAPERSIZE AND THE SCALE
ACCORDING TO THE GIVEN FORMAT :-

```
            PAPERSIZE              SCALE
            ---------              -----

            (INTEGER)              (REAL)

PAPERSIZE = 0,1,2,3,4 FOR A0,A1,A2,A3,A4 SIZES RESPECTIVELY.
  SCALE= ANY POSITIVE VALUE LESS OR EQUAL TO THE FOLLOWING
         LIMITS BASED ON THE SELECTED PAPERSIZE.


  FOR PAPERSIZE A0, MAXIMUM PERMISSIBLE SCALE = 16.41
  FOR PAPERSIZE A1, MAXIMUM PERMISSIBLE SCALE = 10.78
  FOR PAPERSIZE A2, MAXIMUM PERMISSIBLE SCALE =  7.03
  FOR PAPERSIZE A3, MAXIMUM PERMISSIBLE SCALE =  4.22
  FOR PAPERSIZE A4, MAXIMUM PERMISSIBLE SCALE =  2.34
 *** PLEASE INPUT THE PSIZE AND PSCALE ***
 4   2.0


  PAPERSIZE A4     SCALE  2.0 : 1.0




  DO YOU WANT ANY DIMENSIONING?

  ENTER 1 IF YES, OR 0 IF NO.
  1


   DO YOU WISH TO SUPPLY ANY TITLE-BLOCK INFORMATION ?

   ENTER 1 IF YES, OR 0 IF NO.
0





           END OF FINISHED SECTION PROGRAM
           ===============================
```

```
     ROLFORM CAD/CAM SYSTEM
     ======================

     PROGRAM                                    KEYWORD
     =======                                    =======

(1)      INPUT SECTION DATA                     SECTION
(2)      RERUN SECTION ON SCREEN                NSECTION
(3)      RERUN SECTION ON PLOTTER               MSECTION
(4)      INPUT FLOWER PATTERN DATA              FLOWER
(5)      RERUN FLOWER PATTERN ON SCREEN         NFLOWER
(5A)     RERUN FLOWER PATTERN SEPERATELY        SFLOWER
(6)      RERUN FLOWER PATTERN ON PLOTTER        MFLOWER
(7)      RUN TEMPLATE PROGRAM                   TEMPLATE
(8)      RUN TEMPLATE ON PLOTTER                MTEMPLATE
(9)      INPUT ROLL DESIGN DATA                 DESIGN
(9A)     INPUT ROLL D-DATA IN SINGLE STAGE      SDESIGN
(10)     RERUN ROLL DESIGN ON SCREEN            NDESIGN
(11)     RERUN ROLL DESIGN ON PLOTTER           MDESIGN
(12)     RUN WIRE FRAME ON SCREEN               WIRE
(13)     RUN WIRE FRAME ON PLOTTER              MWIRE
(14)     RUN PLAN/SIDE ON SCREEN                VIEW
(15)     RUN PLAN/SIDE ON PLOTTER               MVIEW
(16)      EDIT ROLL DESIGN                      AEDITOR
(17)      INPUT CUTTING COMMANDS                CUTPLOT
(18)      RERUN CUTPLOT ON SCREEN               NCUTPLOT
(19)      RERUN CUTPLOT ON PLOTTER              MCUTPLOT
(20)      RUN POST PROCESSOR                    MFPOST
(21)      CHECK NC TAPE ON SCREEN               CHK
(22)      CHECK NC TAPE ON PLOTTER              MCHK

          TYPE 99 TO EXIT                      (KEYWORD)

     PLEASE TYPE KEYWORD TO SELECT A PROGRAM
                 =======
  CHOICE:FLOWER


               --- FLOWER PROGRAM VERSION 1.1 ---
```

```
                    **** ROLFOM ****
                       ******




     * PLOTTING PROGRAM NO. 2 FOR ROLLED-SECTION *

                  --- FLOWER PATTERNS ---



 ** PLEASE INPUT THE SECTION NO. **
section no. = ?
1861
  ****************************************
  **                                    **
  **        TERMINAL DEFINITION         **
  **        PLEASE INPUT  1,2,3,4       **
  **        (1) FOR T4010               **
  **        (2) FOR T4107              .**
  **        (3) FOR T4113               **
  **        (4) FOR VT125               **
  **                                    **
  ****************************************
2

** INPUT JRUN = 1 IF FLOWER PATTERN ONLY,OR
                2 IF ROLLER-PLOTTINGS ONLY,OR
                3 IF BOTH OF THE ABOVE
 JRUN = ?
3
** INPUT NSTAGE (NSTAGE = TOTAL NO. OF PASS,MAXIMUM 50
 NSTAGE = ?
11
** INPUT JBEND (SELECTION OF CIRCULAR-ELEMENT BENDING
OPTION,
(TYPE 0 IF SIMPLE ELEMENT DEFINITION, OR
      1 IF COMPOSITE PERCENTAGE ELEMENT DEFINITION)
      2 IF AUTOMATIC PERCENTAGE ELEMENT DEFINITION)
  JBEND = ?
0
```

```
-----INPUT THE FOLLOWING :-
PASS    ELEMENT TO   ANGLE   ELEMENT TO   ANGLE
 NO.    BE BENT      OF      BE BENT      OF
        (LEFT)       BENT    (RIGHT)      BENT
(terminate input by typing
0       0             0.0     0            0.0
1       2             0.0     2            0.0
2       2            20.0     2           20.0
2       4            -5.0     2           20.0
3       2            40.0     2           40.0
3       4           -25.0     2           40.0
4       2            60.0     2           60.0
4       4           -45.0     2           60.0
5       2            80.0     2           80.0
5       4           -65.0     2           80.0
6       2            90.0     2           90.0
6       4           -80.0     2           90.0
7       4           -90.0     2           90.0
8       4           -90.0     2           90.0
9       4           -90.0     2           90.0
10      4           -90.0     2           90.0
11      4           -90.0     2           90.0
0       0             0.0     0            0.0
** DO YOU WANT THE OPTION FOR SHARPENING OF INSIDE RADII ?
-- input JSHARP = 0 if radii-sharpening is not required at
all, or
                   1 if stage no. are to be entered
individually, or
                  -1 if all stages except last stage require
sharpening
      **** JSHARP =?
-1
** DO YOU WANT THE FIXED PERCENTAGE OPTION ?
   INPUT THE FOLLOWING :-
LINE    LHS      STAGE   STAGE   RHS     STAGE   STAGE
NO.   ELEMENT    NO.     NO.   ELEMENT  NO.     NO.
        NO.      START  FINISH   NO.    START   FINISH
(skip or terminate the input for this option by typing :
0       0       0       0       0       0       0)
0       0       0          0       0       0       0
 PAPERSIZE A4, MAXIMUM SCALE USED =  0.97
```

END OF FLOWER PATTERN PROGRAM

```
     ROLFORM CAD/CAM SYSTEM
     ======================

     PROGRAM                               KEYWORD
     =======                               =======

(1)   INPUT SECTION DATA                   SECTION
(2)   RERUN SECTION ON SCREEN              NSECTION
(3)   RERUN SECTION ON PLOTTER             MSECTION
(4)   INPUT FLOWER PATTERN DATA            FLOWER
(5)   RERUN FLOWER PATTERN ON SCREEN       NFLOWER
(5A)  RERUN FLOWER PATTERN SEPERATELY      SFLOWER
(6)   RERUN FLOWER PATTERN ON PLOTTER      MFLOWER
(7)   RUN TEMPLATE PROGRAM                 TEMPLATE
(8)   RUN TEMPLATE ON PLOTTER              MTEMPLATE
(9)   INPUT ROLL DESIGN DATA               DESIGN
(9A)  INPUT ROLL D-DATA IN SINGLE STAGE    SDESIGN
(10)  RERUN ROLL DESIGN ON SCREEN          NDESIGN
(11)  RERUN ROLL DESIGN ON PLOTTER         MDESIGN
(12)  RUN WIRE FRAME ON SCREEN             WIRE
(13)  RUN WIRE FRAME ON PLOTTER            MWIRE
(14)  RUN PLAN/SIDE ON SCREEN              VIEW
(15)  RUN PLAN/SIDE ON PLOTTER             MVIEW
(16)   EDIT ROLL DESIGN                    AEDITOR
(17)   INPUT CUTTING COMMANDS              CUTPLOT
(18)   RERUN CUTPLOT ON SCREEN             NCUTPLOT
(19)   RERUN CUTPLOT ON PLOTTER            MCUTPLOT
(20)   RUN POST PROCESSOR                  MFPOST
(21)   CHECK NC TAPE ON SCREEN             CHK
(22)   CHECK NC TAPE ON PLOTTER            MCHK

       TYPE 99 TO EXIT                    (KEYWORD)

     PLEASE TYPE KEYWORD TO SELECT A PROGRAM
                 =======
 CHOICE:DESIGN


              --- ROLL  DESIGN PROGRAM VERSION 1.1 ---
```

```
                                   *** ROLFOM ***
                                       ******

   ** INPUT THE SECTION NO.,PLEASE! **
 section no. = ?
 1861

              * PLOTTING PROGRAM NO.4 FOR ROLLED-SECTION *

                         --- ROLLER PROFILES ---

   ****************************************
   **                                    **
   **        TERMINAL DEFINITION         **
   **        PLEASE INPUT  1,2,3,4       **
   **        (1) FOR T4010               **
   **        (2) FOR T4107               **
   **        (3) FOR T4113               **
   **        (4) FOR VT125               **
   **                                    **
   ****************************************
 4

 ** INPUT JRUN = 1 IF FLOWER PATTERN ONLY,OR
                 2 IF ROLLER-PLOTTINGS ONLY,OR
                 3 IF BOTH OF THE ABOVE
  JRUN = ?
 ** INPUT NSTAGE (NSTAGE = TOTAL NO. OF PASS,MAXIMUM 50
  NSTAGE = ?
 ** INPUT JBEND (SELECTION OF CIRCULAR-ELEMENT BENDING
OPTION,
 (TYPE 0 IF SIMPLE ELEMENT DEFINITION, OR
       1 IF COMPOSITE PERCENTAGE ELEMENT DEFINITION)
   JBEND = ?
```

```
-----INPUT THE FOLLOWING :-
PASS     ELEMENT TO    ANGLE    ELEMENT TO    ANGLE
 NO.     BE BENT       OF       BE BENT       OF
         (LEFT)        BENT     (RIGHT)       BENT
(terminate input by typing
0        0             0.0      0             0.0
** DO YOU WANT THE OPTION FOR SHARPENING OF INSIDE RADII ?
-- input JSHARP = 0 if radii-sharpening is not required at
all, or
                  1 if stage no. are to be entered
individually, or
                 -1 if all stages except last stage require
sharpening
       **** JSHARP =?
** DO YOU WANT THE FIXED PERCENTAGE OPTION ?
   INPUT THE FOLLOWING :-
LINE    LHS      STAGE    STAGE    RHS      STAGE    STAGE
NO.   ELEMENT    NO.      NO.    ELEMENT   NO.      NO.
        NO.      START   FINISH    NO.     START    FINISH
(skip or terminate the input for this option by typing :
0       0        0        0        0        0        0)
DO YOU WANT CONSISTENT PASS-HEIGHTS & C-C DISTANCE?
INPUT IPASHT =  1 IF YES,OR
               -1 IF YOU WANT INCONSISTENT PASS HEIGHTS AND
C-C DISTANCE
IPASHT = ?
-1
PLEASE INPUT THE PASS HEIGHT (PASHT) AND C-C DISTANCE (CTOC)
INPUT PASHT & CTOC FOR STAGE            1PLEASE
 63.5      140.03
INPUT PASHT & CTOC FOR STAGE            2PLEASE
 67.945    152.77
INPUT PASHT & CTOC FOR STAGE            3PLEASE
 67.945    165.43
INPUT PASHT & CTOC FOR STAGE            4PLEASE
 67.945    165.43
INPUT PASHT & CTOC FOR STAGE            5PLEASE
 67.945    179.03
INPUT PASHT & CTOC FOR STAGE            6PLEASE
 67.945    179.03
INPUT PASHT & CTOC FOR STAGE            7PLEASE
 67.945    179.03
INPUT PASHT & CTOC FOR STAGE            8PLEASE
 67.945    165.43
INPUT PASHT & CTOC FOR STAGE            9PLEASE
 67.945    179.03
INPUT PASHT & CTOC FOR STAGE           10PLEASE
 55.245    166.33
INPUT PASHT & CTOC FOR STAGE           11PLEASE
 55.245    166.33
```

```
ITOC=?
 1
 NOW INPUT THE TOLERANCES, WHERE
 TOLLH = LH TOLERANCE BETWEEN ROLLER & LAST ELEMENT,
 TOLRH = RH TOLERANCE BETWEEN ROLLER & LAST ELEMENT.
 INPUT TOLLH & TOLRH PLEASE
 0.15     0.15
 INPUT JTEMP = 1 IF YOU WANT COMPONENT DRAWING IN HIDDEN
LINE,OTHERWISE 0
       RSCALE = DESIRED SCALE FOR THE ROLLER DRAWINGS
       RGAP = THE GAP DIMENSION BETWEEN TOP AND BOTTOM ROLL
NOW INPUT JTEMP,RSCALE & RGAP PLEASE
  0    1.0    20.0
 INPUT JSTAGE(1) =-1 IF ALL STAGES REQ'D FOR ROLLERS,OR
       JSTAGE(1) = 1 IF NO STAGES REQ'D ,OR
       JSTAGE(1) = ANY POSITIVE INTEGER LESS THAN NSTAGE
                   IF SELECTED STAGES REQ'D FOR ROLLERS
JSTAGE(1)=?
  -1
 DO YOU WANT THE PINCH DEIFFERENCE OPTION?
 INPUT JPINCH = 0 IF NO EXTERNAL PINCH DIFFERENCE DIMENSION
                DEFINITION IS SUPPLIED, OR
               1 IF ONLY ONE PINCH DIFFERENCE DIMENSION
DEFINITION IS SUPPLIED FOR ALL BENDING STAGES, OR
              -1 IF PINCH DIFFERENCE DIMENSION DEFINITION IS
SUPPLIED INDIVIDUALLY FOR EACH BENDING STAGE, OR
               2 IF SINGLE THICKNESS OPTION WITH ONE COMMON
CLEARANCE VALUE FOR ALL STAGES SELECTED, OR
              -2 IF SINGLE THICKNESS OPTION WITH INDIVIDUAL
CLEARANCE VALUE FOR EACH STAGE SELECTED.
JPINCH=?
 -1
 INPUT THE PINCH DEFFERENCE DIMENSIONS,WHERE
 PDIM1 = THICKNESS BETWEEN THE DRIVE SURFACES
 PDIM2 = THICKNESS BETWEEN THE CLEARANCE SURFACES
 INPUT PDIM1 & PDIM2 FOR STAGE            1PLEASE
    4.65    4.66
 INPUT PDIM1 & PDIM2 FOR STAGE            2PLEASE
    4.65    4.83
 INPUT PDIM1 & PDIM2 FOR STAGE            3PLEASE
    4.65    4.93
 INPUT PDIM1 & PDIM2 FOR STAGE            4PLEASE
    4.72    5.00
 INPUT PDIM1 & PDIM2 FOR STAGE            5PLEASE
    4.72    5.00
 INPUT PDIM1 & PDIM2 FOR STAGE            6PLEASE
    4.72    5.00
 INPUT PDIM1 & PDIM2 FOR STAGE            7PLEASE
    4.72    5.00
 INPUT PDIM1 & PDIM2 FOR STAGE            8PLEASE
    4.72    5.00
 INPUT PDIM1 & PDIM2 FOR STAGE            9PLEASE
    4.65    5.00
 INPUT PDIM1 & PDIM2 FOR STAGE           10PLEASE
    4.72    5.00
 INPUT PDIM1 & PDIM2 FOR STAGE           11PLEASE
    4.72    5.00
```

```
 NOW INPUT ELEMENT NO. WHICH DEFINES DRIVE SURFACE FOR EVERY
STAGE,
 2 DEFINITION STATEMENTS PER STAGE REQUIRED,WHERE
 ISQP=CURRENT BENDING STAGE SEQUENCE NO.
 IEPL = L.H.S. ELEMENT DEFINING THE DRIVE SURFACE CONTOUR
 IEPR = R.H.S. ELEMENT DEFINING THE DRIVE SURFACE CONTOUR
 (TERMINATE INPUT BY TYPING  0  0  0)
 ISQP  IEPL  IEPR
 1     1     1
 1     1     1
 2     1     1
 2     1     1
 3     1     1
 3     1     1
 4     1     1
 4     1     1
 5     1     1
 5     1     1
 6     1     1
 6     1     1
 7     1     1
 7     1     1
 8     1     1
 8     1     1
 9     1     1
 9     1     1
10     1     1
10     1     1
11     1     1
11     1     1
 0     0     0
**THE NEW PINCH OPTION**
  PLEASE INDICATE WHERE THE CLEARANCE TO BE ADDED
   ENTER 1 FOR OUTSIDE FACES
         2 FOR INSIE FACES
     OR  3 IF EQUALLY DISTRIBUTED ON BOTH FACES
  (1/2/3) ?
 3



 ARE YOU GOING TO CHOOSE THE SIDE ROLL OPTION?
 ENTER ISROL = 1 IF YES,OR
             = 0 IF NO
ISROL = ?
 1

 ENTER IOTOS = 1 IF CONSISTENT ORIGIN TO SIDE-ROLL AXES,OR
              -1 IF INCONSISTENT ORIGIN TO SIDE-ROLL AXES
DISTANCES
IOTOS = ?
 -1
 INPUT ORIGIN TO SIDE-ROLL AXES DISTANCE,WHERE
 OTOSL = DISTANCE BETWEEN ORIGIN AND LEFT SIDE-ROLL CENTRE,
AND
 OTOSR = DISTANCE BETWEEN ORIGIN AND RIGHT SIDE-ROLL CENTRE.
```

```
INPUT OTOSL & OTOSR FOR STAGE 1 PLEASE
 120.0    120.0
INPUT OTOSL & OTOSR FOR STAGE           2PLEASE
120.0    120.0
INPUT OTOSL & OTOSR FOR STAGE           3PLEASE
 120.0    120.0
INPUT OTOSL & OTOSR FOR STAGE           4PLEASE
 120.0    120.0
INPUT OTOSL & OTOSR FOR STAGE           5PLEASE
 135.0    106.0
INPUT OTOSL & OTOSR FOR STAGE           6PLEASE
 133.5    100.0
INPUT OTOSL & OTOSR FOR STAGE           7PLEASE
 127.0    100.0
INPUT OTOSL & OTOSR FOR STAGE           8PLEASE
 148.0    100.0
INPUT OTOSL & OTOSR FOR STAGE           9PLEASE
 120.0    120.0
INPUT OTOSL & OTOSR FOR STAGE          10PLEASE
 136.0    100.0
INPUT OTOSL & OTOSR FOR STAGE          11PLEASE
 136.0    100.0



 INPUT THE SIDE-ROLL CONTOUR DEFINITION, WHERE
 ISQS  = CURRENT BENDING STAGE SEQUENCE NO.,
 IESL1 = L.H.S. ELEMENT CONSTITUTING L.H.S. SIDE-ROLL
CONTOUR,
 IESL2 = WHICH FACE OF THE L.H.S. ELEMENT IS DESIRED,
 IESR1 = R.H.S. ELEMENT CONSTITUTING R.H.S. SIDE-ROLL
CONTOUR,
 IESR2 = WHICH FACE OF THE R.H.S. ELEMENT IS DESIRED.
INPUT ISQS,IESL1,IESL2,IESR1 & IESR2 PLEASE
(TERMINATE INPUT BY TYPING
 0  0  0  0  0 )
5    2    1    2    1
5    5    4    3    1
6    2    1    2    1
6    5    4    3    1
7    2    1    2    1
7    5    1    3    1
8    0    0    2    1
8    0    0    3    1
10   5    4    2    1
10   5    4    3    1
11   5    4    2    1
11   5    4    3    1
0    0    0    0    0
 INPUT SELECTION FOR EXTENSION-CONTOUR OPTION,ENTER
 IEXTN = 1 IF EXTENSION CONTOUR OPTION WILL BE USED
       = 0 IF EXTENSION CONTOUR OPTION WILL NOT BE USED
IEXTN = ?
 1
 INPUT TYPE AND DIMENSION FOR EACH DESIGNATED SIDE-CONTOUR
EXTENSION, WHERE
 ISC1 = SIDE-CONTOUR NO.
```

```
 ISC2 = SIDE-CONTOUR TYPE
 SCDIM1 = DIMENSION DEFINITION FOR SIDE-CONTOUR PART 1
 SCDIM2 = DIMENSION DEFINITION FOR SIDE-CONTOUR PART 2
 SCDIM3 = DIMENSION DEFINITION FOR SIDE-CONTOUR PART 3
 SCDIM4 = DIMENSION DEFINITION FOR SIDE-CONTOUR PART 4
(TERMINATE INPUT BY TYPING
 0  0  0.0  0.0  0.0  0.0 ),NOW INPUT
ISC1  ISC2  SCDIM1  SCDIM2  SCDIM3  SCDIM4
 1     2      0.0    15.0    12.0    20.0
 2     2     16.0     0.0    12.0    20.0
 3     2     13.0    12.7    12.0    20.0
 4     2     13.0    11.5    12.0    20.0
 5     1      0.0    11.0    66.0     0.0
 6     1      0.0    11.0    33.5     0.0
 7     1     11.0    14.5    12.7     0.0
 8     1      0.0    14.0    21.5     0.0
 9     1      0.0    11.0    64.0     0.0
10     1      0.0    11.0    22.5     0.0
11     1     11.0    15.0    12.7     0.0
12     1      0.0    11.5    15.5     0.0
13     1      0.0    11.0    53.0     0.0
14     1      0.0     0.0    11.0    11.0
15     2     12.7     0.0    22.0    17.0
16     2      0.0    11.0    12.0    20.0
17     2      6.5    17.5    16.0     0.0
18     1      0.0    17.5    16.0     0.0
19     1      0.0    21.5    16.0     0.0
20     2     13.0     0.0    12.0    20.0
 0     0      0.0     0.0     0.0     0.0


 INPUT SIDE-CONTOUR SELECTION FOR EACH BENDING STAGEWHERE
 ISQD  = BENDING STAGE NO. FOR WHICH SIDE-CONTOUR DEFINITION
IS INTENDED
 IELD1 = TYPE OF SIDE-CONTOUR ON L.H.S.
 IELD2 = SIDE-CONTOUR NO. WHICH HAS BEEN DEFINED PREVIOUSLY
AND
         IS TO BE SELECTED FOR THIS STAGE NO. ON L.H.S.
 IERD1 = TYPE OF SIDE-CONTOUR ON R.H.S.
 IERD2 = SIDE-CONTOUR NO. WHICH HAS BEEN DEFINED PREVIOUSLY
AND
         IS TO BE SELECTED FOR THIS STAGE NO. ON R.H.S.
 (TERMINATE INPUT BY TYPING
 0  0  0  0  0 ),NOW ENTER
 ISQD  IELD1  IELD2  IERD1  IERD2
 1     2      1      2      1
 2     2      2      2      2
 3     2     20      2      3
 4     2     20      2      4
 5     1      7      1      8
 5     1      5      1      6
 6     1     11      1     12
 6     1      9      1     10
 7     1     14      1     12
 7     1     13      1     10
 8     2     15      1     12
 8     2     15      1     10
 9     2     16      2     17
```

```
10    1   19    1   12
10    1   18    1   10
11    1   19    1   12
11    1   18    1   10
 0    0    0    0    0
                ** INPUT FILE ENDS **
```

***** END OF PROGRAM NO. 4 *****

ROLFORM CAD/CAM SYSTEM
======================

	PROGRAM	KEYWORD
(1)	INPUT SECTION DATA	SECTION
(2)	RERUN SECTION ON SCREEN	NSECTION
(3)	RERUN SECTION ON PLOTTER	MSECTION
(4)	INPUT FLOWER PATTERN DATA	FLOWER
(5)	RERUN FLOWER PATTERN ON SCREEN	NFLOWER
(5A)	RERUN FLOWER PATTERN SEPERATELY	SFLOWER
(6)	RERUN FLOWER PATTERN ON PLOTTER	MFLOWER
(7)	RUN TEMPLATE PROGRAM	TEMPLATE
(8)	RUN TEMPLATE ON PLOTTER	MTEMPLATE
(9)	INPUT ROLL DESIGN DATA	DESIGN
(9A)	INPUT ROLL D-DATA IN SINGLE STAGE	SDESIGN
(10)	RERUN ROLL DESIGN ON SCREEN	NDESIGN
(11)	RERUN ROLL DESIGN ON PLOTTER	MDESIGN
(12)	RUN WIRE FRAME ON SCREEN	WIRE
(13)	RUN WIRE FRAME ON PLOTTER	MWIRE
(14)	RUN PLAN/SIDE ON SCREEN	VIEW
(15)	RUN PLAN/SIDE ON PLOTTER	MVIEW
(16)	EDIT ROLL DESIGN	AEDITOR
(17)	INPUT CUTTING COMMANDS	CUTPLOT
(18)	RERUN CUTPLOT ON SCREEN	NCUTPLOT
(19)	RERUN CUTPLOT ON PLOTTER	MCUTPLOT
(20)	RUN POST PROCESSOR	MFPOST
(21)	CHECK NC TAPE ON SCREEN	CHK
(22)	CHECK NC TAPE ON PLOTTER	MCHK
	TYPE 99 TO EXIT	(KEYWORD)

PLEASE TYPE KEYWORD TO SELECT A PROGRAM

EXIT FROM ROLFORM CAD/CAM SYSTEM

D1861.DAT

(THE FINISHED SECTION FILE)

```
2     2          5.0000      4
     1   1       7.0000     0.0000
     2   2       2.5000    90.0000
     3   1       8.0000     0.0000
     4   2       2.5000   -90.0000
     5   1      32.5000     0.0000
     0   0       0.0000     0.0000
     1   1       7.0000     0.0000
     2   2       2.5000    90.0000
     3   1      25.5000     0.0000
     0   0       0.0000     0.0000
    4    2.0000
  1
  1
 1
 7  EXAMPLE
 3
 4  1861
 6
 8  S.PANTON
 7
 6  1/4/86
 0
```

E1861.DAT

THE FLOWER PATTERN FILE

```
  3
 11
  0
  1     2      0.00     2      0.00
  2     2     20.00     2     20.00
  2     4     -5.00     2     20.00
  3     2     40.00     2     40.00
  3     4    -25.00     2     40.00
  4     2     60.00     2     60.00
  4     4    -45.00     2     60.00
  5     2     80.00     2     80.00
  5     4    -65.00     2     80.00
  6     2     90.00     2     90.00
  6     4    -80.00     2     90.00
  7     4    -90.00     2     90.00
  8     4    -95.00     2     90.00
  9     4    -90.00     2     90.00
 10     4    -90.00     2     90.00
 11     4    -90.00     2     90.00
  0     0      0.00     0      0.00
 -1
    0     0     0     0     0     0     0
```

R1861.DAT

THE ROLL DESIGN FILE

```
-1
   63.500      140.030
   67.945      152.770
   67.945      165.430
   67.945      165.430
   67.945      179.030
   67.945      179.030
   67.945      179.030
   67.945      179.030
   67.945      165.430
   67.945      179.030
   55.245      166.330
  1
    0.150        0.150
 0     1.000    20.000
 -1
 -1
      4.650     4.660
      4.650     4.830
      4.650     4.930
      4.650     5.080
      4.720     5.000
      4.720     5.000
      4.720     5.000
      4.720     5.000
      4.650     5.000
      4.720     5.000
      4.720     5.000
    1   1   1
    1   1   1
    2   1   1
    2   1   1
    3   1   1
    3   1   1
    4   1   1
    4   1   1
    5   1   1
    5   1   1
    6   1   1
    6   1   1
    7   1   1
    7   1   1
    8   1   1
    8   1   1
    9   1   1
    9   1   1
   10   1   1
   10   1   1
```

```
  11    1    1
  11    1    1
   0    0    0
 3
 1
-1
   120.000    120.000
   120.000    120.000
   120.000    120.000
   120.000    120.000
   135.000    106.000
   133.500    100.000
   127.000    100.000
   148.000    100.000
   120.000    120.000
   136.000    100.000
   136.000    100.000
   5    2    1    2    1
   5    5    4    3    1
   6    2    1    2    1
   6    5    4    3    1
   7    2    1    2    1
   7    5    1    3    1
   8    0    0    2    1
   8    0    0    3    1
  10    5    4    2    1
  10    5    4    3    1
  11    5    4    2    1
  11    5    4    3    1
   0    0    0    0    0
 1
  1    2     0.000   15.000   12.000   20.000
  2    2    16.000    0.000   12.000   20.000
  3    2    13.000   12.700   12.000   20.000
  4    2    13.000   11.500   12.000   20.000
  5    1     0.000   11.000   66.000    0.000
  6    1     0.000   11.000   33.500    0.000
  7    1    11.000   14.500   12.700    0.000
  8    1     0.000   14.000   21.500    0.000
  9    1     0.000   11.000   64.000    0.000
 10    1     0.000   11.000   22.500    0.000
 11    1    11.000   15.000   12.700    0.000
 12    1     0.000   11.500   15.500    0.000
 13    1     0.000   11.000   53.000    0.000
 14    1     0.000    0.000   11.000   11.000
 15    2    12.700    0.000   22.000   17.000
 16    2     0.000   11.000   12.000   20.000
 17    2     6.500   17.500   12.000   20.000
 18    1     0.000   17.500   16.000    0.000
 19    1     0.000   21.500   16.000    0.000
 20    2    13.000    0.000   12.000   20.000
  0    0     0.000    0.000    0.000    0.000
  1    2    1    2    1
  2    2    2    2    2
  3    2   20    2    3
  4    2   20    2    4
  5    1    7    1    8
  5    1    5    1    6
```

6	1	11	1	12
6	1	9	1	10
7	1	14	1	12
7	1	13	1	10
8	2	15	1	12
8	2	15	1	10
9	2	16	2	17
10	1	19	1	12
10	1	18	1	10
11	1	19	1	12
11	1	18	1	10
0	0	0	0	0

SAMPLE N.C. LISTING

```
O0101
N10G21
N15G50X-455.000Z410.000M08
N20T0404M42
N25G96S200M03
N30G0X-150.000Z147.338
N35G1X-124.000Z143.538F0.30
N40Z-2.800
N45G0X-128.000Z143.538
N50G1X-118.000
N55Z82.493
N60G0X-122.000Z143.538
N65G1X-112.000
N70Z87.689
N75G0X-116.000Z143.538
N80G1X-106.000
N85Z92.886
N90G0X-110.000Z143.538
N95G1X-100.000
N100Z98.082
N105G0X-104.000Z143.538
N110G1X-94.000
N115Z103.278
N120G0X-98.000Z143.538
N125G1X-93.518Z144.538
N130Z141.538
N135Z128.538
N140Z103.695
N145X-118.065Z82.437
N150G2X-118.306Z81.987I0.780K-0.450
```

APPENDIX B

DERIVATION OF GARDINERS EQUATION

Let

E = Modulus of elasticity

r = Radius of curvature after springback

R= Radius of curvature before springback

S = Stress

Y = Yield stress

t = Thickness

X = Location measured from neutral axis, positive in tension direction

θ = Angle

ε = Strain

Δ = Change

and subscripts :

f = final	o = original
x at location (x)	y at yield point

Assuming :

a) That the neutral axis is midway through the sheet metal

b) That the material is elastic perfectly plastic

c) That there is no stress at the neutral axis

d) That the strain in a fibre is proportional to its distance from the neutral axis

Subsequently, the strain at any fibre can be expressed as follows

$$\varepsilon=[(R+X)\delta\theta-R\delta\theta]/(R\delta\theta)=X/R$$

and,

original strain $\varepsilon_0=X/R$

final strain $\varepsilon_f=X/r$

change in strain $\varepsilon_0-\varepsilon_f=X[(1/R)-(1/r)]$

This gives :

$$\Delta S=EX[(1/R)-(1/r)]$$

Yield occurs when $X=X_y$, where $Y=X_y(E/R)$ or $X_y=Y(R/E)$, this subsequently leads to the following expressions.

Original stress :

$$S_0=[(XE)/R]_{X=0}^{X=X_y} \quad \text{and} \quad [Y]_{X=X_y}^{X=t/2}$$

Final stress :

$$S_f=S_0-\Delta S=[(XE)/R]-\{EX[(1/R)-(1/r)]\} \quad \text{where } 0<X<X_y$$

and

$$Y-\{EX[(1/R)-(1/r)]\} \quad \text{where } X>X_y$$

or rewriting -

$$[(XE)/r]_{X=0}^{X=X_y} \quad \text{and} \quad [Y-\{EX[(1/R)-(1/r)]\}]_{X=X_y}^{X=t/2}$$

respectively.

Since, it is necessary that all forces (Stresses) at a cross section be in static equilibrium, (a) the sum of all the stresses be equal to zero; (b) the sum of all the moments of the stresses be equal to zero.

By symmetry, it will be seen that the forces on either side of the axis will be equal and opposite, hence summing to zero thus satisfying condition (a) automatically. The other condition is the balance of moments which is

$$\int_{-t/2}^{t/2} XS_x \delta X=0$$

Again by symmetry the value of XS_x will be equal in sign and magnitude at a given distance on either side of the neutral axis. Therefore the moment of stress on one side of the neutral axis must be zero.

$$\int_{0}^{t/2} XS_x \delta X=0$$

or

$$\int_{0}^{X_y} XS_x \delta X + \int_{X_y}^{t/2} XS_x \delta X =0$$

where $X_y=(YR)/E$

After integation and simplification, this gives :

$$(R/r)=1-3[(RY)/(ET)]+4[(RY)/(ET)]^3$$

APPENDIX C

PROOF THAT THE THICKNESS STRESS IS ZERO

To prove that the thickness stress is zero it is necessary to prove that , (1) the thickness stress is zero at the yield point and (2) that successive increments of stress in the thickness direction are zero.

At the yield point :

$$\sigma_x = E((1-\nu)\varepsilon_x + \nu\, \varepsilon_y)/((1+\nu)(1-2\nu))$$

$$\sigma_y = E((1-\nu)\varepsilon_y + \nu\, \varepsilon_x)/((1+\nu)(1-2\nu))$$

$$\sigma_z = E(\nu\varepsilon_x + \nu\, \varepsilon_y)/((1+\nu)(1-2\nu))$$

(Where symbols have the same meaning as section 7.6.2)

Since $\varepsilon_x = -\varepsilon_y$

$$\sigma_z = 0, \quad \sigma_x = -\sigma_y = E((1-2\nu)\varepsilon_y)/((1+\nu)(1-2\nu)$$

Therefore :

$$\sigma_z' = (1/3)(2\sigma_z - (\sigma_x+\sigma_y)) = 0 \qquad (1)$$

$$\sigma_x' = (1/3)(2\sigma_x - \sigma_y)$$

$$\sigma_y' = (1/3)(2\sigma_y - \sigma_x)$$

Since $\sigma_x = -\sigma_y \qquad \sigma_x' = -\sigma_y'$ (2)

After an increment of strain $\delta\varepsilon_x, \delta\varepsilon_y$ Where $\delta\varepsilon_x = -\delta\varepsilon_y$

$$\delta\sigma_z = E(((\nu/(1-2\nu))-(\sigma_x'\sigma_z'/S))\delta\varepsilon_x + ((\nu/(1-2\nu))-(\sigma_y'\sigma_z'/S))\delta\varepsilon_y)/(1+\nu) \qquad (3)$$

Since $\sigma_z' = 0$ and $\delta\varepsilon_x + \delta\varepsilon_y = 0 \qquad \delta\sigma_z = 0$

Therefore σ_z still equals zero after an increment of strain. From considering Eqn (3) σ_z will always remain zero if the value of σ_z' remains zero. By considering Eqn (1) σ_z' will always equal zero if σ_x equals $-\sigma_y$. σ_x will always equal $-\sigma_y$ providing $\delta\sigma_x$ equals $-\delta\sigma_y$.

And

$$\delta\sigma_x = E(((\nu/(1-2\nu))-(\sigma_x'\sigma_y'/S))\delta\varepsilon_y + (((1-\nu)/(1-2\nu))-(\sigma_x'\sigma_x'/S))\delta\varepsilon_y)/(1+\nu)$$

$$\delta\sigma_y = E(((\nu/(1-2\nu))-(\sigma_x'\sigma_y'/S))\delta\varepsilon_x + ((1-\nu)/(1-2\nu))-(\sigma_y'\sigma_y'/S))\delta\varepsilon_y)/(1+\nu)$$

Since from Eqn (2) $\sigma_x' = -\sigma_y'$ $(\sigma_x')^2 = (\sigma_y')^2$

Therefore when $\delta\varepsilon_x = -\delta\varepsilon_y$ $\delta\sigma_x = -\delta\sigma_y$

Therefore the thickness stress will remain zero.

APPENDIX D

EXAMPLE SESSION OF LIMITED INPUT FLOWER PATTERN PROGRAM

```
    ROLFORM
    -------

  LIMITED INPUT FLOWER PATTERN PROGRAM
  ------------------------------------

  THIS PROGRAM IS IN 3 SECTIONS

 (1) INPUTTING OF COMPULSARY PASS`S
   (AND AUTOMATIC GENERATION OF INTERMEADIATE PASS`S
 (2) THE INTERACTIVE EDITOR
   FOR EDITING THE COMPUTER GENERATED FLOWER PATTERN)
 (3) THE PERCENTAGE COMPOSITE ELEMENT LENGTH OPTION
   (FOR CONTROLLING THE MEANS OF FORMING BENDS


 THESE STAGES MUST BE PERFORMED SEQUENTIALLY
 HOWEVER,THE SOFTWARE HAS BEEN DESIGNED SO THAT
 THE DESIGNER MAY EXIT THE  PROGRAM AFTER ANY STAGE
 AND MAY LATER RERUN THE PROGRAM OMITTING THE STAGES
 THAT HE CONSIDERS FINISHED


 PLEASE INPUT THE STAGE YOU WISH TO START AT
   1,2 OR 3


 PLEASE INPUT SECTION NUMBER
1ch
 PLEASE INPUT YIELD STRESS AND ELASTIC CONSTANT
  IN MN/M**2
 FOR INSTANCE STEEL 280.0 207000.0 MN/M**2
280.0,207000.0


  ********************************************
  **                                        **
  **   THIS PROGRAMME TAKES COMPULSARY      **
  **   FLOWER PATTERN PASSES (INPUT BY THE  **
  **   DESIGNER) AND GENERATES INTERMEDIATE **
  **   PASSES BY THE FORMING ANGLE THEORY   **
  **                                        **
  ********************************************
```

```
 ** INPUT NSTAGE (TOTAL NUMBER OF COMPULSARY STAGES
  NSTAGE = ?
1
 ** THE SECTION IS A SYMMETRICAL SECTION **
 -----THUS INPUT THE FOLLOWING :
 PASS      ELEMENT TO         ANGLE OF
  NO.      BE BENT(RIGHT)     BEND
 (terminate input by typing
  0        0                  0.0)
1   2   90.0
0   0   0.0
  PAPERSIZE A4, MAXIMUM SCALE USED =  2.39

     PLEASE INPUT PASS LENGTH
200.0

     PLEASE INPUT FORMING ANGLE
1.25

     PLEASE INPUT MAXIMUM POWER IN HP
1.0

     PLEASE INPUT VELOCITY IN M/SEC
1.0


   PLEASE INPUT "CONSTANT" ELEMENT
3
    PLEASE INPUT "VIEWING ANGLE"
70.0

 PRESS RETURN TO PROCEED TO THE INTERACTIVE EDITOR
 TYPE   EXIT   TO END SESSION


 THE PURPOSE OF THIS PROGRAM IS TO ALLOW INTERACTIVE
  EDITING OF THE COMPUTER PRODUCED FLOWER PATTERN

      MENU A
      ======

  PLEASE INPUT 1-5

 1 TO PLOT FLOWER PATTERN
 2 TO RUN WIRE FRAME VIEW
 3 TO EXAMINE FLOWER PATTERN DATA
 4 TO EDIT FLOWER PATTERN DATA
 5 TO FINISH SESSION
4
```

```
 PASS ELL   ANGL     ELR   ANGR
 1    2     31.15    2     31.15
 2    2     44.66    2     44.66
 3    2     55.11    2     55.11
 4    2     64.63    2     64.63
 5    2     73.39    2     73.39
 6    2     81.76    2     81.76
 7    2     90.00    2     90.00
 0    0      0.00    0      0.00

    MENU B
    ======

  PLEASE INPUT 1-3
   1 TO EDIT FLOWER PATTERN
   2 TO EXIT EDITOR WITHOUT UPDATING
   3 TO EXIT EDITOR AND UPDATE
1


    MENU C
   ======

    EDITING OPTIONS
   PLEASE INPUT 1-4

 1 TO INPUT A NEW PASS
 2 TO DELETE A EXISTING PASS
 3 TO ALTER A EXISTING PASS
 4 TO FINISH EDITING
1

 INPUT THE PASS NUMBER BEFORE THE PASS YOU WISH
 TO INSERT
3

 PLEASE INPUT
 LHS EL,LHS ANG,RHS EL, RHS ANG
 TERMINATE BY TYPING 0,0.0,0,0.0
2,20.0,2,20.0
0,0.0,0,0.0

    MENU C
   ======

    EDITING OPTIONS
   PLEASE INPUT 1-4

 1 TO INPUT A NEW PASS
 2 TO DELETE A EXISTING PASS
 3 TO ALTER A EXISTING PASS
 4 TO FINISH EDITING
2
```

```
 ARE YOU SURE YOU WISH TO DELETE A PASS (Y/N)
Y
 INPUT PASS NUMBER YOU WISH TO DELETE
3

    MENU C
   ======

    EDITING OPTIONS
   PLEASE INPUT 1-4

 1 TO INPUT A NEW PASS
 2 TO DELETE A EXISTING PASS
 3 TO ALTER A EXISTING PASS
 4 TO FINISH EDITING
3

 PLEASE INPUT PASS NUMBER
2
 PLEASE INPUT 1 FOR LHS OR 2 FOR RHS
1
 PLEASE INPUT BEND NUMBER
2
THE ANGLE YOU ARE EDITING =     44.6600
 PLEASE INPUT NEW ANGLE
45.0

    MENU C
   ======

    EDITING OPTIONS
   PLEASE INPUT 1-4

 1 TO INPUT A NEW PASS
 2 TO DELETE A EXISTING PASS
 3 TO ALTER A EXISTING PASS
 4 TO FINISH EDITING
4


    MENU B
    ======

  PLEASE INPUT 1-3
  1 TO EDIT FLOWER PATTERN
  2 TO EXIT EDITOR WITHOUT UPDATING
  3 TO EXIT EDITOR AND UPDATE
2
```

```
      MENU A
      ======

  PLEASE INPUT 1-5

 1 TO PLOT FLOWER PATTERN
 2 TO RUN WIRE FRAME VIEW
 3 TO EXAMINE FLOWER PATTERN DATA
 4 TO EDIT FLOWER PATTERN DATA
 5 TO FINISH SESSION
5

 PRESS RETURN TO PROCEED TO THE EL LENGTH OPTION
 TYPE   EXIT   TO END SESSION

***** YOU'VE SELECTED THE AUTOMATIC COMPOSITE ELEMENT OPTION
*****
    INPUT MAX PERMISSIBLE SPRINGBACK (%)
2.0
    ISEQ  = BENDING STAGE SEQUENCE NO.
    IELML = LEFT-HAND ELENENT(CIRCULAR) TO BE BENT
    XANGL = CUMULATIVE ANGLE OF BENDING FOR THE LEFT-HAND
ELEMENT
    IELMR = RIGHT-HAND ELEMENT(CIRCULAR) TO BE BENT
    XANGR = CUMULATIVE ANGLE OF BENDING FOR THE RIGHT-HAND
ELEMENT
   ----- input the following data :-
 ISEQ  IELML  XANGL    IELMR  XANGR
 (terminate input by typing
   0    0    0.0      0    0.0
    LEFT HAND SIDE
 PASS NUMBER  1
 ELEMENT NUMBER  2
 ANGLE =       31.1500
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100           0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE  ***
 ***  INPUT 1 IF YOU WISH TO EDIT     ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE  ***
0
    RIGHT HAND SIDE
 PASS NUMBER  1
 ELEMENT NUMBER  2
 ANGLE =       31.1500
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100           0
```

```
 ***  ARE ELEMENT LENGTHS ACCEPTABLE   ***
 ***  INPUT 1 IF YOU WISH TO EDIT      ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE   ***
0
  ISEQ  IELML  XANGL  IELMR  XANGR
    LEFT HAND SIDE
 PASS NUMBER  2
 ELEMENT NUMBER  2
 ANGLE =       44.6600
     PERCENTAGES IN
 trailing element,bend element,leading element
          0          100            0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE   ***
 ***  INPUT 1 IF YOU WISH TO EDIT      ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE   ***
0
    RIGHT HAND SIDE
 PASS NUMBER  2
 ELEMENT NUMBER  2
 ANGLE =       44.6600
     PERCENTAGES IN
 trailing element,bend element,leading element
          0          100            0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE   ***
 ***  INPUT 1 IF YOU WISH TO EDIT      ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE   ***
0
  ISEQ  IELML  XANGL  IELMR  XANGR
    LEFT HAND SIDE
 PASS NUMBER  3
 ELEMENT NUMBER  2
 ANGLE =       55.1100
     PERCENTAGES IN
 trailing element,bend element,leading element
          0          100            0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE   ***
 ***  INPUT 1 IF YOU WISH TO EDIT      ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE   ***
0
    RIGHT HAND SIDE
 PASS NUMBER  3
 ELEMENT NUMBER  2
 ANGLE =       55.1100
     PERCENTAGES IN
 trailing element,bend element,leading element
          0          100            0
```

```
 ***  ARE ELEMENT LENGTHS ACCEPTABLE   ***
 ***  INPUT 1 IF YOU WISH TO EDIT      ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE   ***
0
  ISEQ  IELML  XANGL  IELMR  XANGR
    LEFT HAND SIDE
 PASS NUMBER  4
 ELEMENT NUMBER  2
 ANGLE =       64.6300
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100            0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE   ***
 ***  INPUT 1 IF YOU WISH TO EDIT      ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE   ***
0
    RIGHT HAND SIDE
 PASS NUMBER  4
 ELEMENT NUMBER  2
 ANGLE =       64.6300
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100            0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE   ***
 ***  INPUT 1 IF YOU WISH TO EDIT      ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE   ***
0
  ISEQ  IELML  XANGL  IELMR  XANGR
    LEFT HAND SIDE
 PASS NUMBER  5
 ELEMENT NUMBER  2
 ANGLE =       73.3900
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100            0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE   ***
 ***  INPUT 1 IF YOU WISH TO EDIT      ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE   ***
    RIGHT HAND SIDE
 PASS NUMBER  5
 ELEMENT NUMBER  2
 ANGLE =       73.3900
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100            0
```

```
 ***  ARE ELEMENT LENGTHS ACCEPTABLE  ***
 ***  INPUT 1 IF YOU WISH TO EDIT     ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE  ***
0
  ISEQ  IELML  XANGL  IELMR  XANGR
    LEFT HAND SIDE
 PASS NUMBER  6
 ELEMENT NUMBER  2
 ANGLE =       81.7600
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100           0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE  ***
 ***  INPUT 1 IF YOU WISH TO EDIT     ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE  ***
0
    RIGHT HAND SIDE
 PASS NUMBER  6
 ELEMENT NUMBER  2
 ANGLE =       81.7600
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100           0

 ***  ARE ELEMENT LENGTHS ACCEPTABLE  ***
 ***  INPUT 1 IF YOU WISH TO EDIT     ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE  ***
0
  ISEQ  IELML  XANGL  IELMR  XANGR
    LEFT HAND SIDE
 PASS NUMBER  7
 ELEMENT NUMBER  2
 ANGLE =       90.0000
     PERCENTAGES IN
 trailing element,bend element,leading element
          0         100           0
  SPRINGBACK=     INSIDE RADIUS=
   0.37DEGREES      1.00MM

 ***  ARE ELEMENT LENGTHS ACCEPTABLE  ***
 ***  INPUT 1 IF YOU WISH TO EDIT     ***
 ***  INPUT 0 IF THEY ARE ACCEPTABLE  ***
0
```

```
   RIGHT HAND SIDE
PASS NUMBER  7
ELEMENT NUMBER  2
ANGLE =       90.0000
    PERCENTAGES IN
trailing element,bend element,leading element
         0          100           0
 SPRINGBACK=     INSIDE RADIUS=
  0.37DEGREES      1.00MM

***  ARE ELEMENT LENGTHS ACCEPTABLE  ***
***  INPUT 1 IF YOU WISH TO EDIT     ***
***  INPUT 0 IF THEY ARE ACCEPTABLE  ***
0
```

APPENDIX E

N.C PROGRAM FOR SCRIBING GRID USING BRIDGEPORT INTERACT SERIES 1 MILLING MACHINE

```
TOOL DEF 1                          L 0.0   R 0.0
          Z 0.0
TOOL CALL 1                                 R 0.0  F 100  M03
X 0.0  Y 0.0                                R 0.0  F 300
LBL 1
          Z -2.01                                  F 100
          Z  0.0                                   F 100
LBL 0
      Y (P1)
LBL 2
X 0.0                                              F 500
CALL LBL1
X 20.0                                             F 500
CALL LBL1
X 40.0                                             F 500
CALL LBL1
X 60.0                                             F 500
CALL LBL1
X 80.0                                             F 500
CALL LBL1
X 100.0                                            F 500
CALL LBL1
X 120.0                                            F 500
CALL LBL1
X 140.0                                            F 500
CALL LBL1
X 160.0                                            F 500
CALL LBL1
X 180.0                                            F 500
CALL LBL1
X 200.0                                            F 500
CALL LBL1
X 220.0                                            F 500
CALL LBL1
X 240.0                                            F 500
CALL LBL1
CALL LBL0
X 0.0       Y (P2)                                 F 500
CALL LBL2
X 0.0       Y (P3)                                 F 500
CALL LBL2
X 0.0       Y (P4)                                 F 500
CALL LBL2
X 0.0       Y (P5)                                 F 500
```

```
CALL LBL2
X 0.0        Y (P6)                                  F 500
CALL LBL2
X 0.0        Y (P7)                                  F 500
CALL LBL2
X 0.0        Y (P8)                                  F 500
CALL LBL2
X 0.0        Y (P9)                                  F 500
CALL LBL2
X 0.0        Y (P10)                                 F 500
CALL LBL2
X 0.0        Y (P11)                                 F 500
CALL LBL2
X 0.0        Y (P12)                                 F 500
CALL LBL2
X 0.0        Y (P13)                                 F 500
CALL LBL2
X 0.0        Y (P14)                                 F 500
CALL LBL2
X 0.0        Y (P15)                                 F 500
CALL LBL2
X 0.0        Y (P16)                                 F 500
CALL LBL2
X 0.0        Y (P17)                                 F 500
CALL LBL2
X 0.0        Y (P18)                                 F 500
CALL LBL2
X 0.0        Y (P19)                                 F 500
CALL LBL2
STOP                                                      M 02
```

NOTE :- THE VALUES P1:P19 ARE VARIABLES DEFINED BY TABLE 9.2

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