OPERATION SEQUENCING FOR SHEET METAL PARTS

A DISSERTATION

Submitted in partial fulfilment of the
requirements for the award of the degree
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MECHANICAL ENGINEERING
(With Specialization in Production and Industrial System Engineering)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work being presented in this thesis entitled **"OPERATION SEQUENCING FOR SHEET METAL PARTS"** towards partial fulfillment of the requirement for the award of the degree of **MASTER OF ENGINEERING** in **MECHANICAL ENGINEERING** with specialization in **PRODUCTION AND INDUSTRIAL SYSTEMS ENGINEERING** submitted to the Mechanical and Industrial Engineering Department, University of Roorkee, is an authentic record of my own work carried out during the period June' 1999 to March' 2000 under the supervison of **Dr. N.K. Mehta,** Professor, and **Dr. P.K. Jain,** Assistant Professor, Department of Mechanical and Industrial Engineering, Unviersity of Roorkee.

The matter contained in this thesis has not been submitted by me for the award of any other degree or diploma.

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CERTIFICATION

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Sheet metal pressworking operations have a long past history. With technological advancements, pressworking operations have also achieved large scale automation. In order to incorporate flexibilities and reduce change over time in the present era of small batch production of complex components, CAPP was introduced in pressworking operations.

In the present work, a methodology for generation of operation sequences has been proposed. It involves selection of operation steps by which the features can be produced on the part without violating the relevant technological constraints.

A single sequence of operations may not be appropriate for all situations in a changing production environment, with multiple objectives such as maximizing machine utilization and minimizing number of tool changes. Keeping this in mind, a methodology has been developed for generating feasible operation sequences, satisfying the tolerance and dimensional criteria, for pressworking operations on mild steel sheet components.

An interactive computer program in 'C' language has been written to generate operation sequences for components containing upto 7 different group of features. These operation sequences are evaluated for the number of tool setup changes and machine changes required and the total time needed for producing a part.Functioning of the software has been ascertained by case studies.

Recommendations for future work have also been made on the basis of the present work.

NOMENCLATURE

α_b = Angle of bend, degree

α_f = Angle of flange, degree

a = Length of flanged portion on the draw, mm

c = Intercent of edge line, on y-axis, mm

c.c = Center to center distance amongh sheared features, mm

C = Drawing force constant

d = Diameter force constant d = diameter of hole, mm.

d_c = Cup diameter, mm

D = Blank diameter, mm.

dt = Distance between features, mm

f = Force, N

f_p = Pad force, N

h = Cup height, mm

h.h = Distance between hole edges, mm

h.sl-ax = Distance between hole and slot edge along slot axis, mm

h.sl-per = Distance between hole and slot edge along perpendicular to slot axis, mm

h.sl = Distance between hole and slot edges, mm

l = Length of cut, mm

l_b = Bend length, mm

l_f = Flange length, mm

L = Span, mm
m = Slope of edge line
p = Perimeter of cut, mm
P = Percentage penetration
r_a = Plastic strian ratio
r_b = Radius of bend, mm
r_{bo} = Bottom curve radius, mm
r_h = Radius of hole, mm
r_f = Radius of flange, mm
s = Shear on punch or die
S = Shearing strength, N/mm^2
S_c = Compressive strength of metal, N/mm^2
t = Sheetmetal thickness, mm
t_0 = Initial thickness of specimen, mm
t_1 = Die clearance, mm
w = Width of cut, mm
W = Width of sheet metal at bend, mm
W_0 = Initial width of specimen, mm
(x_0,y_0) = Center co-ordinates for circular blank
(x_r,y_r) = Reference co-ordinates for the blank

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CHAPTER - 1
INTRODUCTION

The techniques of sheet metal press working have a long past history. It emerged with the development of steel industry. In fact, to a large extent we owe our present standard of living to the stamped metal parts. Sheet metal parts are widely used in consumer, automobile and a host of other industries. Some of these applications have been discussed in Chapter 2. Pressworking processes have been automated by means of advanced die designs, like, progressive dies, compound dies, transfer dies, etc. for mass production of large number of similar parts.

With the growing trend of larger product variety and smaller production lots, the need for flexibilities in the process has increased to reduce the time of the concept-design-finished product cycle. In particular, to reduce the time spent in process planning, CAPP was introduced in press working processes. Process planning involves systematic determination in detail of methods by which parts can be converted economically and competitively from initial stage (raw material) to the final stage (finished product).

In any CAPP, selection of the operation sequence is one of the most critical activities for manufacturing a part as per the technical specifications. A fixed sequence of opertions will generally not be the best suited from the standpoint of various criterions such as quality and machine utilization. Thus, the aim should be to generate feasible operation sequences which can be suitable for the desirable manufacturing constraints.

The task of operation sequencing in CAPP is influenced by a number of choices in the opertion and the various constraints, such as accessibility for machining a feature, adherance to the spacefied geometry, required holding to acheive tolerance specifications etc. Requirements for the final shape and functional requirements of the component can also be represented as constraints. Some operation parameters affecting the final shape of the component and the geometerical constraints affecting opertion sequences have been discussed in Chapter 2.

In the present work, a methodology has been proposed for generating operation sequences for pressworking operations on sheet metal parts. An interactive computer program in 'C' language has been developed to generate the operation sequences for various press working operations, containing upto 7 features. These opertion sequences have been consequently evaluated for the number of tool setup changes required, machine changes needed and time used in producing a part(manufacturing time).

CHAPTER - 2
OPERATIONS ON SHEET METAL

Press working Operations on sheet metals parts can largely be classified into four broad categories [2]

(i) Sheet metal cutting operations
(ii) Sheet metal forming operations
(iii) Sheet metal drawing operations
(iv) Miscellaneous operations

Within each categories there are a number. of different press working operations. Each of these categories is discussed below.

2.1 SHEET METAL CUTTING OPERATIONS

In sheet metal cutting operations the metal parts are separated by applying a shear force which develop stresses greater than the shearing strength of the sheet metal to be cut.

Cutting edges to cut the metal are provided by the punch (inner cutting edge) and the die (which acts as outer cutting edge).

2.1.1.Theory of Cutting [1,5]

As the punch contacts the work material supported by the die, the pressure gradually builds up. Once the elastic limit of work material is exceeded, the material begins to flow plastically (plastic deformation). A radius is formed on the top edge of hole and the bottom edge of the slug, (of blank) known as "Rollover" whose magnitude depends upon ductility of work material Fig.[2.1]. Compression of the slug material against walls of the die opening burnishes a portion of the edge of the blank. At the same time, plastic flow pulls the material around the punch, causing a corresponding burnished area in the work material Fig.[2.1(b)].

As the punch pressure increases, fracture begins at the cutting edges of the punch and die. Under ideal conditions, these fractures meet and the remaining portion (slug) breaks away Fig.[2.1(c)]. A slight tensile burr will be formed along the top edge of the slug and the bottom edge of the work material Fig.[2.1(d)]. Various portions of holes and the blanks formed by the cutting action are depicted in the Fig.[2.2].

2.1.2. Clearance [1,2,5]

Is defined as an intentional space provided between the punch and die cutting edge and expressed as the amount of clearance per side. Clearance is necessary to allow the fractures to meet when break occurs.

The diameter of the blank is determined by the burnished area. Since, burnished area on the blank is produced by the walls of the die, the blank diameter is equal to the diameter of the die. Similarly, for the pierced hole, the burnished area in the hole, determines the hole diameter.

Therefore, if the blank is to become the work piece, the die diameter is made to blank size and the punch is reduced in size by an amount equal to the die clearance. On the ohter hand, if the pierced hole is to become work piece, the punch is made to the correct hole size and die is made oversized by an amount equal to the die clearance.

2.1.3 Spring back [1,5]

During metal cutting some metal grains are stressed to a point below the elastic limit. Therefore, when cutting is completed these grains "Spring Back" to their original shape. This spring back causes the hole left in the sheet metal to reduce in diameter and grip tightly onto the punch.

The part cutout, i.e, blank, increases in diameter due to spring back and grips tightly inside the die opening.

To avoid the blank from getting stuck in the die, an angular clearance is provided on the latter and the sheet sticking to the punch is removed by means of a stripper.

2.1.4. Cutting Force Calculation

Calculation of cutting force is necessary for selection of the press for shearing operation.

Cutting force without shear :

For the punches and dies without shear, the minimum cutting force required is calculated as follows [2].

Force = shearing strength x area

where,

Area = perimeter of cut x sheet metal thickness.

Thus,

$$F = S.p.t. \qquad ...(2.1.1)$$

For rectangular cuts $F = S \times 2\,(l+w) \times t$

For circular cuts $F = S \times \pi\, d\, t$

where,

F = cutting force, N
S = shearing strength, N/mm^2
t = sheet metal thickness, mm
p = perimeter of cut, mm
L = length of cut, mm
W = width of cut, mm
d = diameter of cut,mm

Cutting force with shear :

Shear is defined as the vertical rise or drop in a cutting edge caused by angle provided on the punch or die cutting edges to reduce the cutting force necessary to shear off the blank (or produce the hole).

If shear is ground on the punch, the strip remains flat but part cutout is highly curled. When shear is ground on the die, the strip is distorted but the blank remains flat. Thus, if part cut is the required product, the shear is provided on the die, and vise versa when the required product is a strip [2] Fig.[2.3].

$$F = \frac{W}{(P+t)+s} \qquad \text{...(2.1.2)}$$

where,

F = cutting force, N
P = percentage penetration
s = shear on the punch/die

Various sheet metal cutting operations have been classified as below [2]

(A) Operations for producing blanks

- * Shearing
- * Cutoff
- * Parting
- * Blanking

(B) Operations for cutting holes

- * Punching
- * Slotting
- * Perforating

(C) Operations for progressive working

- * Notching
- * Semi-notching
- * Lancing
- * Parting

(D) Miscellaneous metal cutting operations

- * Trimming
- * Shaving
- * Slitting etc.

(a) Shearing

Here cutting action is along a straight line. It is used for the following purposes Fig.[2.4]

* to cut strip or coiled stock to blanks
* to cut strip or coiled stock into smaller strips to feed into a blanking or cut off die.
* to trim large sheets, thereby squaring the edges of the sheet.

(b) Blanking

The cutting action is about a complete contour during blanking. Blanking operation for cutting blanks from strip of sheet metal produces excessive scrap Fig.[2.5].

(c) Punching

When holes are produced in the blank or the manufactured product the operation is called punching Fig.[2.6].

(d) Slotting

This is similar to punching, except that here there is cutting of elongated or rectangular holes Fig.[2.7].

(e) Perforating

It consists of a group of punched or slotted holes. The holes may be cut simultaneously or in progressive dies. Normally, perforated holes are equally spaced or are placed in a definite pattern Fig.[2.8].

(f) Notching

Cutting operations during which the punch does not cut on all sides are called notching. They are done for following purposes Fig.[2.9]:

- to free sheet metal for drawing or forming while still attached to the strip (progressive die).
- to cut progressively the blank contour, which is too difficult to obtain on a blanking die.

(g) Lancing

It is a combined bending and cutting operation along a line in the work material. In a progressive die it permits bends or drawing while the part is attached to the strip or coil of the sheet metal Fig.[2.10].

2.2. SHEET METAL FORMING OPERATIONS

During forming, forces are applied on the sheet metal blank to cause permanent change of contour. Forming stresses in the metal are above the elastic limit but below its ultimate tensile strength. Besides, these stresses are acting on the localized areas only. The metal on the outside of curvature is stretched, and experiences tensile stress, whereas the inside curvature is under compressive stress.

Bending is the simplest of forming operations from analytical point of view, and hence has been described here. But the theory applies equally well to other forming operations.

2.2.1 Neutral Axis [1,5]

As the sheet metal is stressed in tension on one surface and in compression on the other, a reversal of stresses must occur. Near the center of the metal thickness, the stresses reduce and approach zero. This plane of zero stress is called neutral plane.

The length of the neutral axis remains unchanged during bending operations. It is measured as a certain distance from inside of the sheet metal at the bend area. Characteristics of the neutral axis are as follows :

* if sheet metal thickness is constant then the neutral axis shifts towards inside of the bend or compression side as the bend radius decreases.
* if bend radius is constant, then the neutral axis shifts closer to the tension side as the sheet metal thickness decreases.

2.2.2 Metal Flow

Since the metal at the bend area is under stresses above the yield stress, some metal flow occurs. Tensile stress causes metal flow that reduces thickness, while compressive stress causes metal flow to increase with width at the bend. But for sheet metals, width is usually many times the thickness which resists plastic flow due to compressive forces. Instead, they cause additional tension on the opposite side of the bend. Increased tensile stress results in increased thinning of sheet metal at the bend therefore, failure occurs more frequently in bending of sheet metal. Wrinkling may occur only when bending (or forming) heavy sheet metals.

2.2.3. Metal Movement [2,5]

During forming operations one area of the blank is usually held stationary on the die as the punch forces the other area up or down to complete the change in the contour. Metal forced up or down by punch moves through space to occupy a new position.

When forming in progressive steps, this metal movement should be known during each step to design succeeding steps correctly. Because of metal movement, larger area is held stationary and smaller area is moved by punch to help in better operation control.

2.2.4 Spring Back [1,2]

Metal near the neutral axis is stressed to points below the elastic limit. When forming forces are removed, this metal tries to return to its original shape. This causes some amount of elastic recovery resulting in some degree of springback.

Various springback characteristics are -

* harder metals cause more spring back
* softer metals cause less springback
* smaller bend radius causes more springback
* larger degree of bend causes more springback
* thicker metal causes more springback

Several methods are employed to overcome or counteract spring back Fig.[2.11]. These are:

(a) over bending (b) bottoming

(c) stretch-forming.

2.2.5. Bending Force [2]

Bending force required to bend the sheet metal in two bends is Fig.[2.12].

$$F = 0.67x\frac{SWt^2}{L} \quad \ldots(2.2.1)$$

for die performing double-bend

and $$F = 0.33\ x\frac{SWt^2}{L} \quad \ldots(2.2.2)$$

for die performing a single bend.

where,

t = sheet metal thickness, mm

W = sheet metal width at bend, mm

L = span, i.e., unsupported length of sheet metal, mm

S = nominal tensile strength, N/mm^2

2.2.5 Pad Force

To hold the metal flat in the area next to the bend, the pad must exert a sufficient force. Pad force is higher for harder metals with higher tensile strength [2]. For soft metals, pad force is lower.

$$F_p = 0.67\ SWt \quad \ldots(2.2.3)$$

2.2.6. Blank Development

When metal is formed, the length of part when measured at the neutral axis is the same as the length in flat position. Therefore

$$\text{Bend length} = \frac{\text{Degree of Bend}}{360} \times 2\pi\,(r + 0.4t) \qquad \ldots(2.2.4)$$

Hence, Blank length = l + b + Bend length

Various sheet metal forming operations are [1,2].

1. Bending	2. Flanging
3. Hemming Fig.[2.19]	4. Seaming
5. Curling Fig.[2.16]	6. Crimping
7. Bulging	8. Corrugating
9. Beading	10. Embossing Fig.[2.18]
11. Forming	

(1) Bending

It is uniform straining of sheet around a straight axis which lies in the neutral plane and is normal to lengthwise direction of the sheet or strip Fig.[2.13].

Different bending methods are shown in Fig.[2.14]

(a) V-bending (b) Edge bending

(c) U-bending

(2) Flanging

It is similar to the bending operation, except that the amount formed down (or up) is small in relation to the remainder of the part.

A flange is used to strengthen the edges of sheet metal parts. It also adds rigidity to the edge and smoothens the sharp edges left by the cutting operations. Often, parts are flanged to aid in assembly, as the flanges may be welded, riveted etc. Various flanges are shown in Fig.[2.15].

(8) Corrugating

Sheet metal is corrugated to add stiffness or rigidity Fig.[2.17], usually in airplanes and trucks. The corrugations reduce contact area between the cargo and the floor and also provide run ways for spillage. Corrugated sheets are also used in radiators for automobiles. They also form major components of refrigerators and heat exchangers.

2.3. SHEET METAL DRAWING OPERATIONS

Drawing is the name given to operations producing cups, shells, boxes, and similar articles from metal blanks.

The theory of cup drawing is discussed to illustrate the principles of drawing [1,2]. Blank required for cup is round.

The blank is placed in a draw die, where the punch pushes the blank through the die. On the return stroke, the cup is stripped from the punch by the counter bore in the bottom of die. Punch has an air vent to prevent vacuum from being formed when the part is stripped from the punch. A drawing operation is referred to as shallow drawing when the depth of the cup is less than half its diameter and deep drawing when the depth is more than half its diameter. Deep drawing is often accompanied by an operation called ironing, which is defined as the reduction in wall thickness of a shell by forcing it through a tight die. Due to ironing, walls are both lengthened and made thinner while the thickness of shell bottom remains unchanged.

2.3.1. Metal Flow

Drawing consists mainly of metal flow through the opening provided by clearance between the punch and die, and the die and blank holder [2].

To study the metal flow, the blank is divided into sections for easy reference Fig[2.20]. Section 1 which forms the bottom of the cup remains undistorted during drawing. A small section is wrapped around the punch radius and as the drawing continues, metal flows over the die radius and straightens. Thus, the outside edge of the blank is drawn towards the punch. In order to accomplish this successfully, the sections of the blank must reduce in circumference and the only way to do this is for the metal to compress and become thicker. Metal may tend to wrinkle rather than compress, especially in thin sheets or with deeper draws. Hence, a blank holder is used to prevent the formation of wrinkles in this case. There must be enough force on the blank holder to prevent formation of wrinkles. The force exerted by the blank holder also increases the frictional forces. Too much blank-holder pressure may therefore tear the side wall of the drawn up.

Following are the important factors affecting metal flow during drawing :

* radius on punch
* draw radius on die
* friction
* metal to be drawn

2.3.2 Forces during drawing

Forces acting during drawing are caused by the following factors [2]

1. bending at the radii.
2. friction between
    a. blank holder and sheet metal.

b. die steel and sheet metal.

c. punch steel and sheet metal.

3. compression at flange area of extremity of the cup.

Drawing force

During drawing, the cup side wall is in tension. Hence, drawing force is calculated based on tensile strength of the metal.

$$F = C\pi d_C t\ S_t \qquad \ldots(2.3.1)$$

where,

C = Drawing force constant

= 0.52 for low-carbon cold-rolled deep drawing steel.

d_C = Cup diameter, mm

t = Sheet metal thickness, mm

S_t = Ultimate tensile strength, N/mm^2

Blank holding force

= 1/3 Drawing force

Ironing force

Burnishing action occurs on both the inside and the outside surfaces of the cup wall as the metal is forced through reduced clearance between the punch and die. This is called Ironing of the cup wall.

$$F = S_c \pi d_c (t-t_1) \qquad \ldots(2.3.2)$$

where,

S_c = compressive strength of metal, N/mm^2

t_1 = die clearance, mm

Total force to be excepted by press is

Press force = Drawing force + Blank holding force + Ironing force.

2.3.3. Blank Diameter

Blank diameter required to produce a cup after drawing is calculated based on principle of constant surface area.

$$D = \sqrt{d_c^2 + 4 d_c h} \qquad \ldots(2.3.3)$$

where,

D = blank diameter, mm

d_c= cup outside diameter, mm

h = cup height, mm

The calculated blank diameter is enhanced to provide allowance for trimming.

2.3.4 Percent Reduction

When the final blank diameter is known, the next step is to determine the percent reduction necessary to convert the blank to the desired cup. If the allowed percent reduction for drawing does not produce the final desired cup size, then redraws must be made. The severity of cupping is determined by the relationship between the punch steel diameter and the blank diameter. Percent reduction is an expression of this severity [2].

$$\% \text{ Reduction} = \frac{D-d}{d} \times 100 \qquad \ldots(2.3.4)$$

Theoretically maximum percent reduction for drawing is about 50 percent. Various sheet metal drawing operations are classified on the basis of the shape of the drawn part. Drawn part shapes fall into the following categories [2].

1. Cupping
    a. Draw
    b. Redraw Fig.[2.21]
    c. Reverse Redraw Fig.[2.22]
2. Box Drawing
    a. Draw
    b. Redraw
3. Panel Drawing-Shallow
    a. Draw
    b. Redraw
4. Panel Drawing-Deep
    a. Draw
    b. Redraw

2.4 FACTORS AFFECTING SHEET METAL OPERATIONS

The important parameters affecting sheet metal operations are [7].

1. plastic zone
2. material properties before press working
3. material properties after press working
4. contact zone

5. tool
6. work piece and surrounding atmosphere
7. press working machine
8. factory

These parameters also interact with each other.

2.4.1. Plastic zone

In plastic zone the material is stressed above the elastic limit, but below the ultimate tensile strength. Shearing commences when the stress exceeds, this limit.

Also, with the increasing strain rate, tool stressing increases due to growing yield stress. So, the load on the tool is decided based on the maximum stress reached in the plastic zone.

2.4.2. Contact zone

Various factors like tool-work interface, clearances, punch-die radius affect the loads on the punch and the material properties obtained after sheet metal operations.

2.4.3. Tool

Appropriate punch-die set should be designed for a sheet metal operation, based on metal properties, work piece thickness, dimensional requirements, lot size etc.

Thickness of work piece, and safety requirements etc. are some of the factors that should be taken care of while planning for a sheet metal operation.

The machine to be used, its power rating, capacity etc., are planned based on the load on tool and the production quantity etc.

All these factors also have a direct or indirect bearing on factory level activities. In this study main emphasis is on the II & III parameters.

2.5.4 Material properties before press working operations

On the basis of previous discussions it can be said that, for shearing operations, the metal characteristics should be such that it easily shears off, leaving few burrs behind. On the other hand, for metal forming and drawing operations plastics deformation of metal should be possible without any cracking under the influence of external load.

Various material properties affecting the steel metal operations are listed below [7].

(A) Metallurgical Properties

* Lattice structures
* Micro structure
* Homogeneity
* Grain size
* Texture

(B) Mechanical properties

* Yield stress
* Tensile strength
* Hardness
* Reduction of area

- * Toughness
- * r_a-value (Anisotropy)
- * n-value (Strain-hardening)

Effect of the general metal properties on the sheet metal operations have been discussed below .

Effect on sheet metal shearing operations

In sheet metal shearing operations, the forces applied on the metal by the punch and die are basically shear forces creating shear stresses. Micro studies of shearing operations show that the grains elongate during shearing operations [2]. So it can be said that sheet metal under shear forces actually fails by tensile stresses.

As the yield strength or hardness increases, forces on the tool also increase and spring back of the blank and pierced part may occur. But softer steels have more ductility and form burrs so they should be blanked with reduced punch-die clearance.

Anisotropy causes directional properties in the metal [6]. Tensile strength may vary as much as 20% between the rolling direction and the transverse direction (it is greater parallel to rolling direction). Due to variations in mechanical properties the cutting properties also vary in grain oriented steels. Cutting across the rolling direction results in a clean break, but the edges are smeared when cutting is parallel with the rolling direction. Thus, punch die clearance also becomes more critical on the sides parallel with the rolling direction.

Effect on the sheet metal forming operations

During forming operations, the sheet metal is stressed above the yield point but safely below the ultimate tensile strength so as to avoid any cracks.

High hardness sheet metals cause more rapid die wear than the relatively softer metals [6]. Other factors, such as presence of scale on the surface of hot-rolled unpickled steels causes two to five times more wear. However, scaled surfaces cause less galling . Soft brass and aluminium cause less wear and galling than does carbon steel. Stainless steels and heat resistance alloys cause more wear and galling. High strength-low alloyed steels, because of their higher strength and lower ductility are more difficult to bend than plain carbon steels. It may be necessary to remove shear burrs and to smooth corners in the area of the bend.

Temper of the metal affects the minimum bend radius [6]. Steel with high temper (low hardness and high ductility) can be bent 180 to a sharp radius without cracks or tears.

Thickness of work piece also affects the pressure to be applied by the dies. Thicker sheets require more pressure as compared to that required by a thinner sheet of the same metal. Both abrasive wear of tool and galling increases with increasing sheet thickness.

Location of burr on the work piece also affects the forming operation [3]. It is undesirable for the burr side to be on the outer surface of formed piece because burr drags around bending radius and into the die opening. This causes, excessive wear of the die members. Whereas, if the burr is on the inner surface, it faces the punch and as there is no draft between the work piece and the punch, the burr cannot erode the latter. Besides, if the burr side is on the outer surface of bend (tension side), the stock material is more susceptible to the initiation of edge fractures in the bend area.

Orientation of the bend with respect to grain direction of anisotropy is also an important affecting parameter [4,6]. Sharper bends can be made across than parallel with the rolling direction, with out cracking of the work material. When bends are to be made in two or more directions, the blank (or piece) should be oriented such that none of the bends is parallel with the rolling direction.

Effect on the sheet metal drawing operations

Drawability of metal depends on two factors [6]

- ability of a material in the flange region to flow easily in the plane of the sheet under shear.
- ability of side wall material to resist deformation in the thickness direction.

As the punch prevents side the wall material from changing dimensions in the circumferential direction, the only way the side materials can flow is by elongation and thinning. Thus ability of the side wall material to withstand the load imposed by its resistance to thinning and high flow strength in the thickness direction is desirable.

Plastic strain ratio 'r_a' compares strengths in the plane and thickness directions by determining true strains in these directions in a tension test. For a sheet tensile test specimen, r_a-value is defined as :

$$r_a = \frac{\ln (W_0/W)}{\ln(t_0/t)} \qquad \ldots(2.5.1)$$

where,

W & t = current width and thickness of specimen, mm

W_0 & t_0 = initial width and thickness of specimen, mm

Because of anisotropic nature, properties of sheet metal vary in different directions. Therefore, average strain ratios are expressed as :

$$\bar{r} = \frac{r_{0^\circ} + r_{45^\circ} + r_{90^\circ}}{4} \qquad \ldots(2.5.2)$$

where,

r_{0° = strain ratio in longitudinal direction

r_{45° = strain ratio at 45° to rolling direction

r_{90° = strain ratio in the transverse direction

If strength in the thickness direction of the sheet is greater than the average strength in the other directions, then in the plane of sheet, $r > 1$. In this case, the material resists uniform thinning and hence deep draws can be achieved.

Variation of flow strength in the plane of sheet is termed planar anisotropy which is measured by "Δr" as

$$\Delta r = \frac{r_{0^\circ} + r_{90^\circ} - r_{45^\circ}}{2} \qquad \ldots(2.5.3)$$

This planar anisotropy causes undesirable "Earing" of work material. Variation of strength in different directions causes formation of ears on the drawn part. Hence, enough extra metal should be left on the drawn cup so that ears can be trimmed.

Grain size of the sheet metal affects the drawability of sheet metals, and it may affect the selection of a grade of the steel [6]. Grain size of ASTM 5 or coarser may result in excessive surface roughness as well as reduced drawability. Surface finish also influences drawability. The dull finish normally supplied on drawing steels is designed to hold lubricants and improve drawability.

2.5.5 Material properties after operation

Various material properties desired after sheet metal operations also affect other press working variables [2]. Few of them are listed below.

* Surface finish
* Edge requirements
* Dimensional accuracy
* Tolerances

On the basis of final shape to be obtained by the work piece, the initial blank size is determined as has been discussed for the forming and drawing operations. For holes and slots, the blank size is determined by leaving a minimum required margin between their edge and the blank border.

Here, our main concern is with the dimensional accuracy and tolerance criteria of geometric features. From the part print, the process engineer determines the critical dimensions. These are applied on those areas of the part which must be held to close tolerances, best surface finish, or are baseline of dimensioning. Critical dimensions are also important for proper functioning of the part, accuracy after assembly and better clamping and locating of work piece [2]. Because these dimensions and features require special attention during operation, they help the process engineer to determine the sequence of operations, select the equipment and tooling necessary and identify the points to be used for location.

Sheet metal working operations are classified into several categories on the basis of their functions or purpose [2]. In one part, the operation may fall the category of critical operations, while on a different part, the same operation may fall into another category. So, categories are made by purpose not by the operation. These categories of sheet metal working operations are discussed below

(a) Critical operations

Are those, used to produce critical dimensions or surfaces. Due to precision required, these operations receive special attention while determining the operation sequence. Critical operations are required to obtain the closeness of tolerance, establish baseline of dimensioning and identifiy the features required for accurate location and clamping of the part.

(b) Non-critical operations

Are the operations involved in producing features with large tolerances, which determine the location and clamping of work piece or the relation of the part produced with other making parts. These operations are necessary for production of part, but difficulty is not expected in controlling the operation. They also do not incur much cost as compared to the critical operations.

(c) Tie-in operations

These operations are performed on sheet metal parts in order to restore the characteristics of metal or the features made on the part.

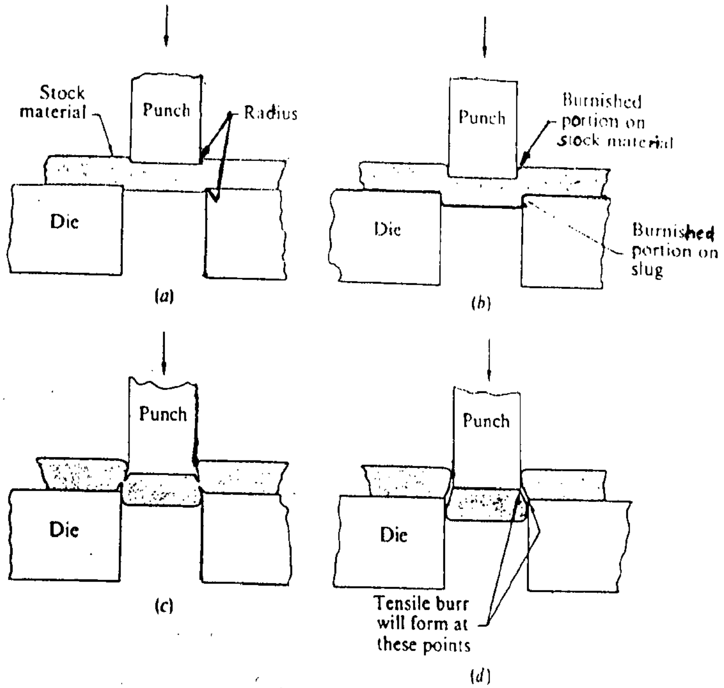


FIGURE 2.1
Cutting-action progression when blanking or piercing metal.

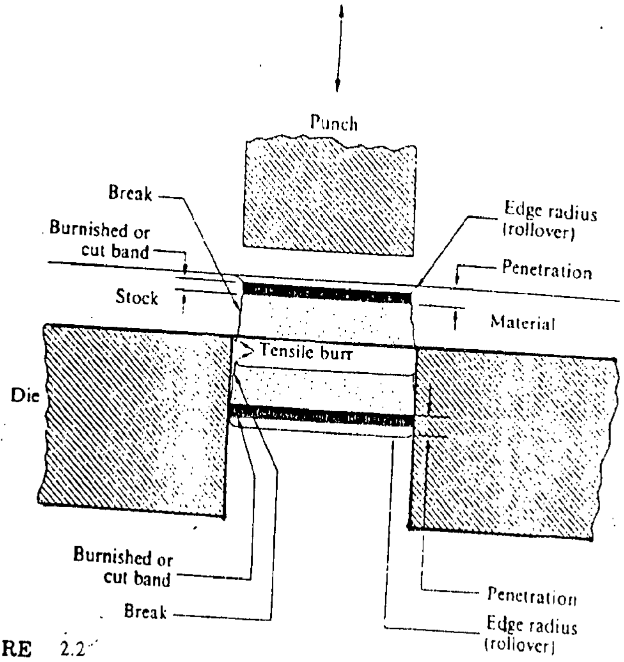


FIGURE 2.2
Characteristic appearance of edges of parts produced by piercing and blanking.

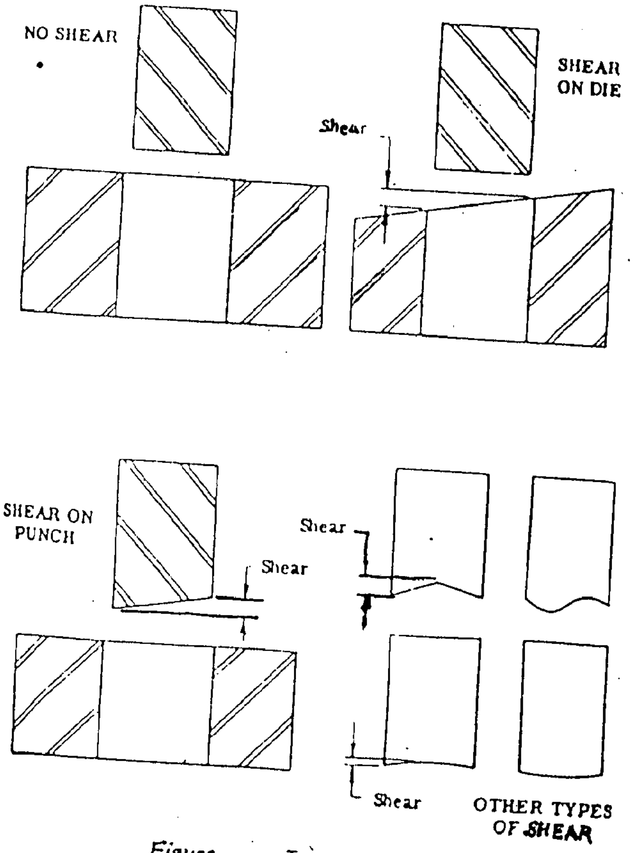


Figure 2.3 Types of Shear

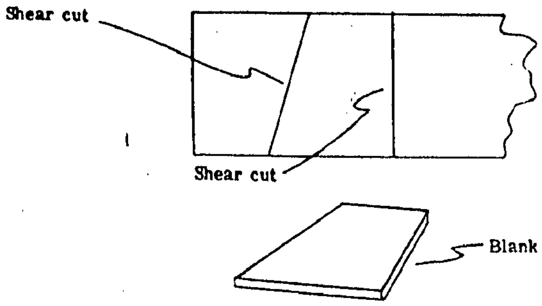


Figure 2.4 Uses of Shearing

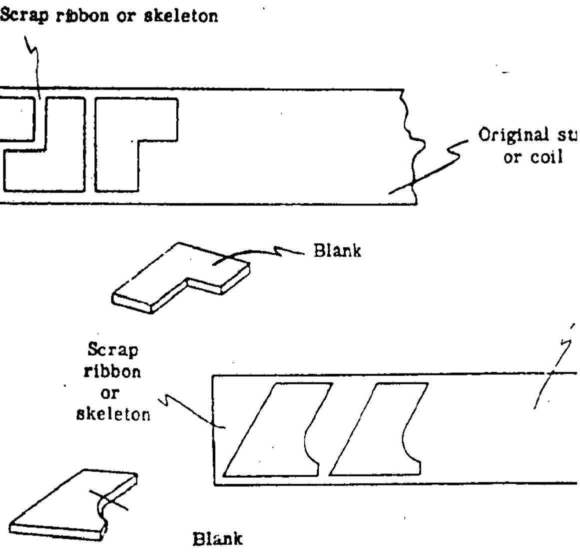


Figure 2.5 Types of Blanking

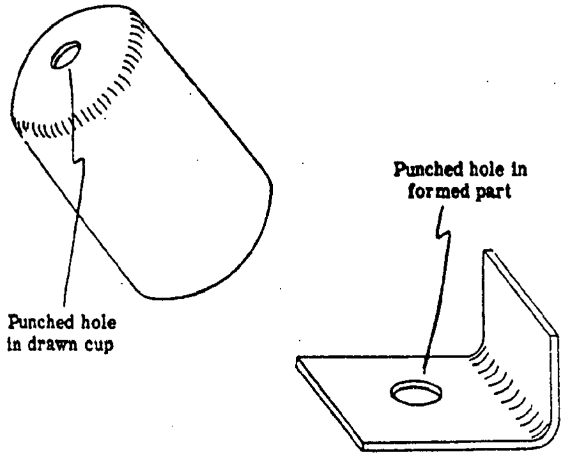


Figure 2.6 Types of Punching

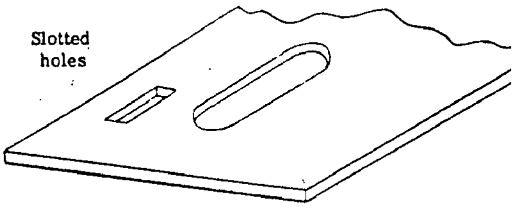
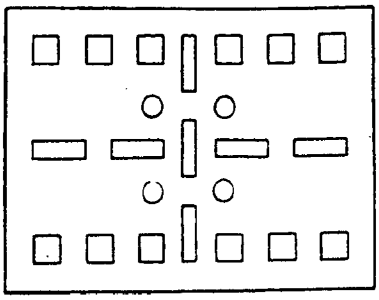


Figure 2.7 Slotting



Note that a group of perforated holes need not be of the same size or shape.

Figure 2.8 Perforated Parts

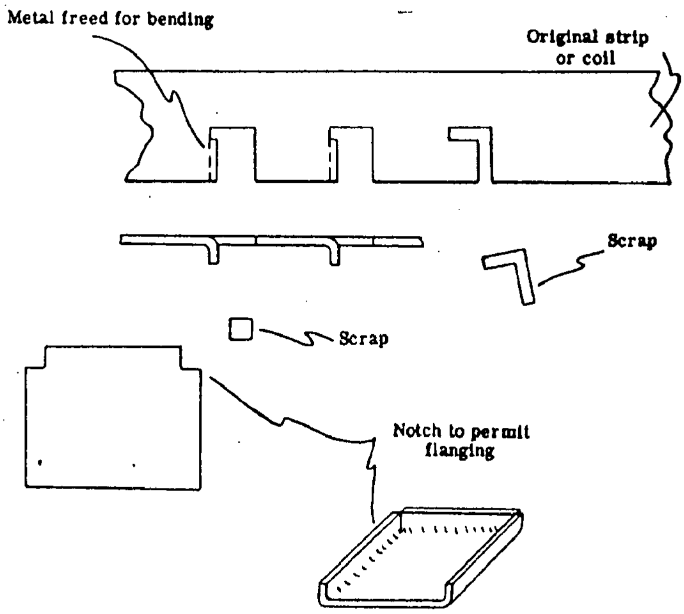


Figure 2.9: Uses of Notching

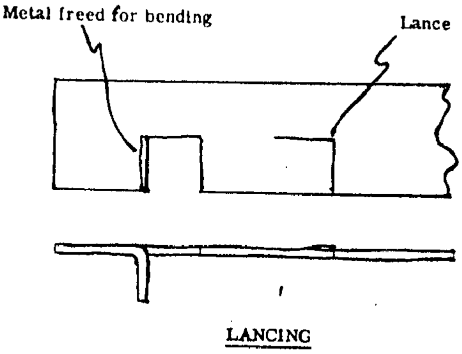
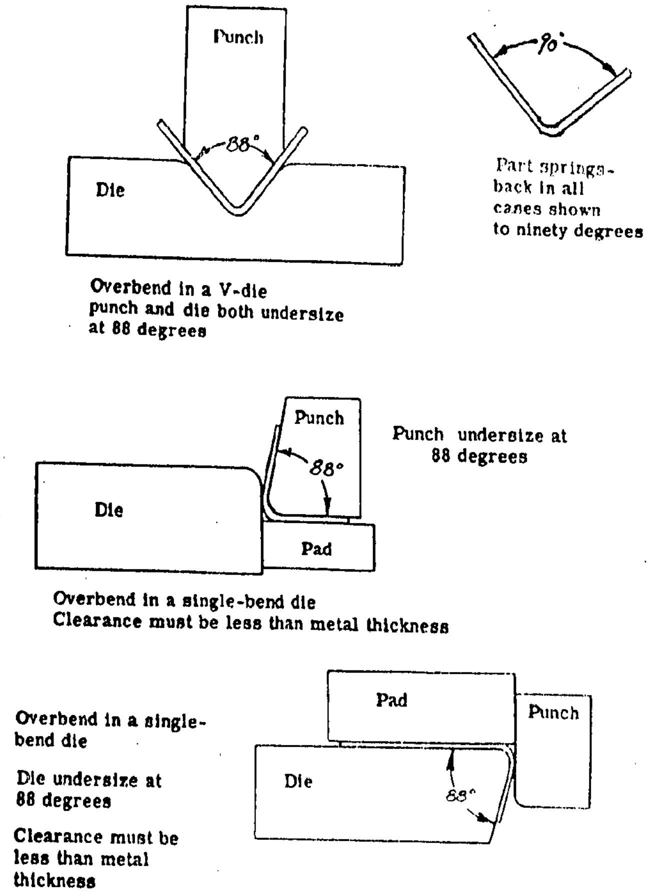


Figure 2.10 Lancing,



Part springs-back in all cases shown to ninety degrees

Overbend in a V-die punch and die both undersize at 88 degrees

Punch undersize at 88 degrees

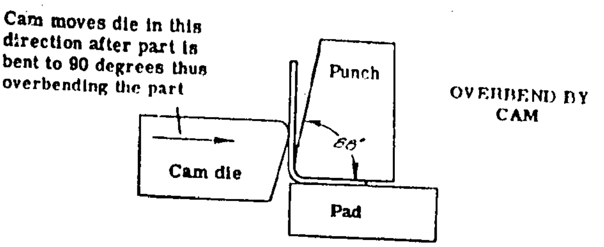
Overbend in a single-bend die
Clearance must be less than metal thickness

Overbend in a single-bend die

Die undersize at 88 degrees

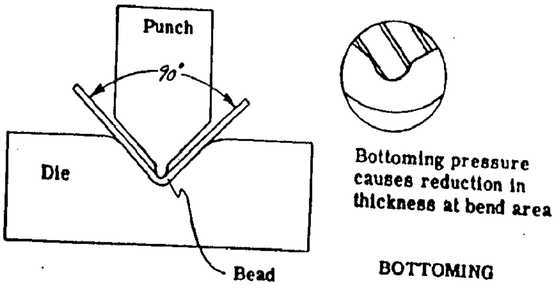
Clearance must be less than metal thickness

Overbending



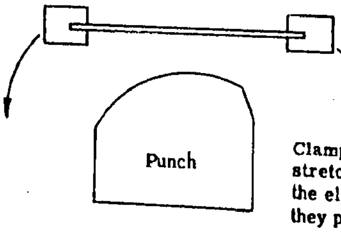
Cam moves die in this direction after part is bent to 90 degrees thus overbending the part

OVERBEND BY CAM



Bottoming pressure causes reduction in thickness at bend area

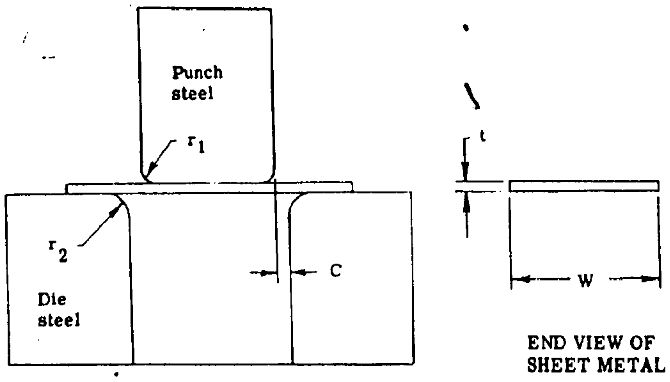
BOTTOMING



STRETCH-FORMING

Clamps grip and stretch metal beyond the elastic limit as they pull sheet metal over the punch contour

Figure 2.11 Overcoming Springback



$$L = r_1 + C + r_2$$

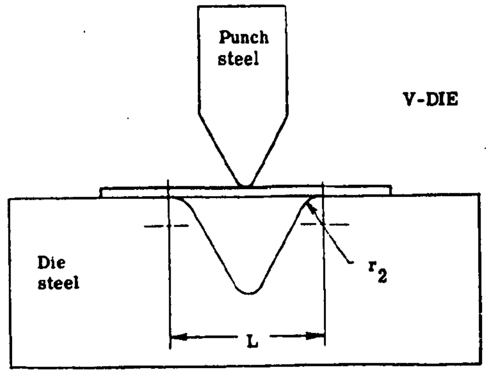


Fig. 2.12 Bending Force

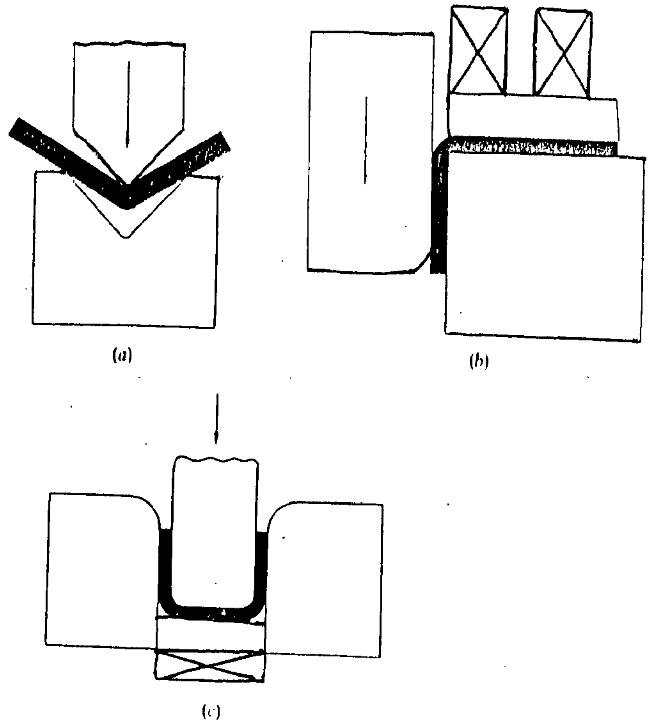
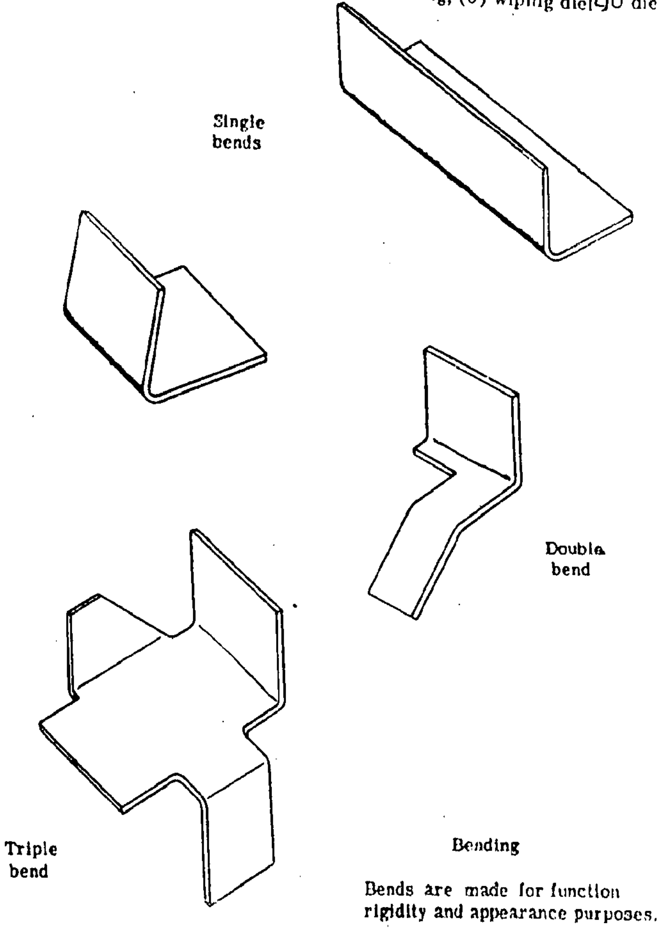

(*a*) (*b*) (*c*)

FIGURE 2.13
Methods of bending sheet metal: (*a*) V bending, (*b*) wiping die(*c*)U die (channel die).



Bending

Bends are made for function rigidity and appearance purposes.

Figure 2.14 Types of Bending

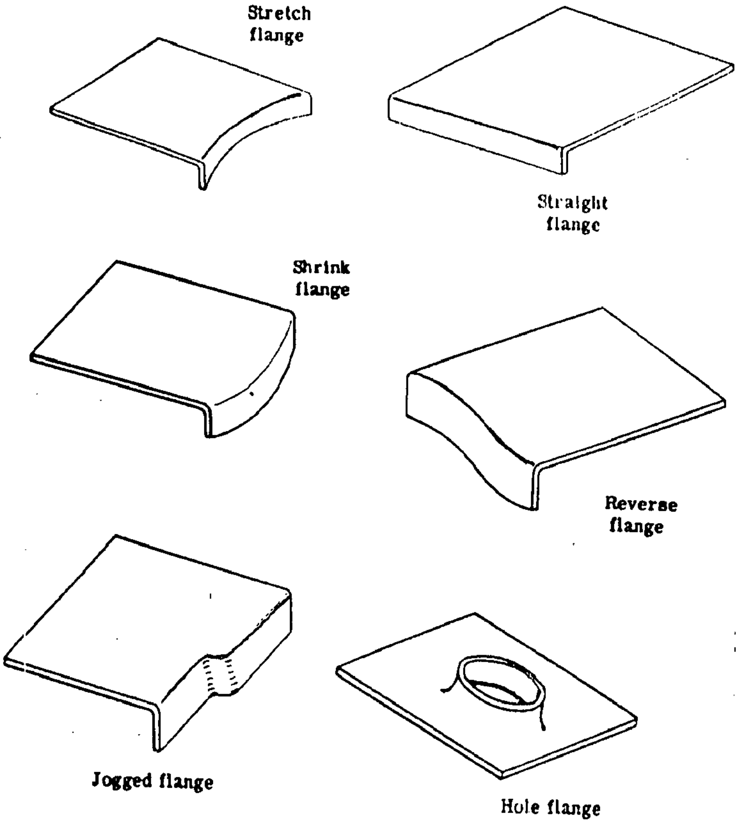


Figure 2.15 Flanging

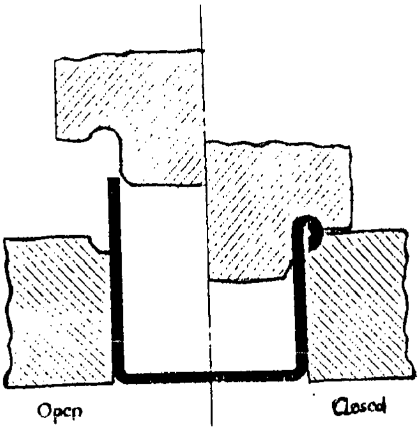


FIGURE 2.16
Principle of curling die.

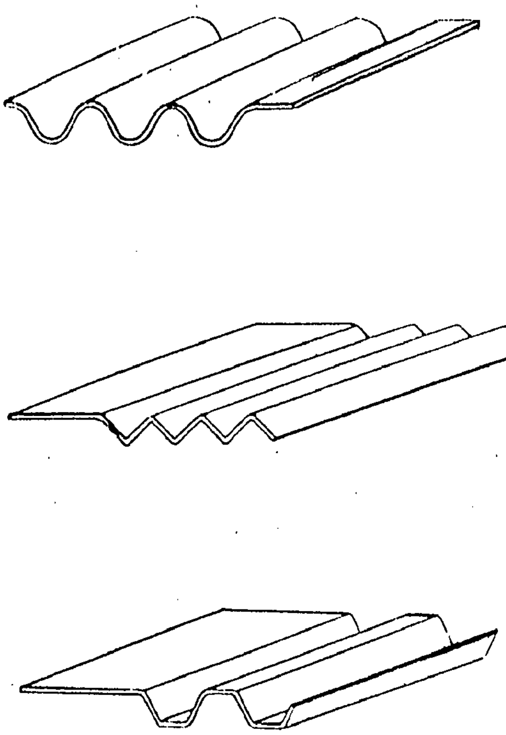
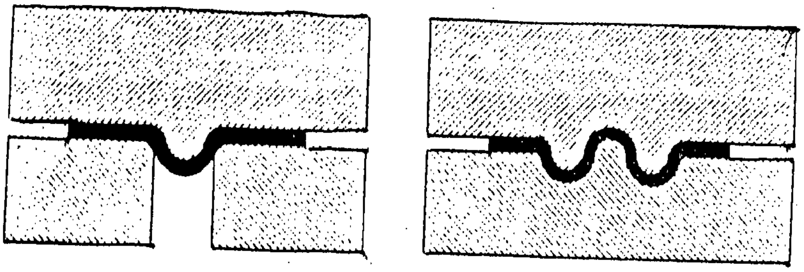


Figure 2.17 Examples of Corrugating



(a)

(b)

FIGURE 2.18
Embossing dies.

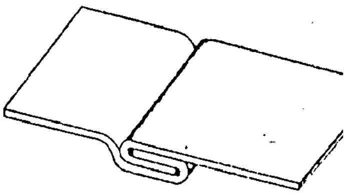


Figure 2.19 Hemming

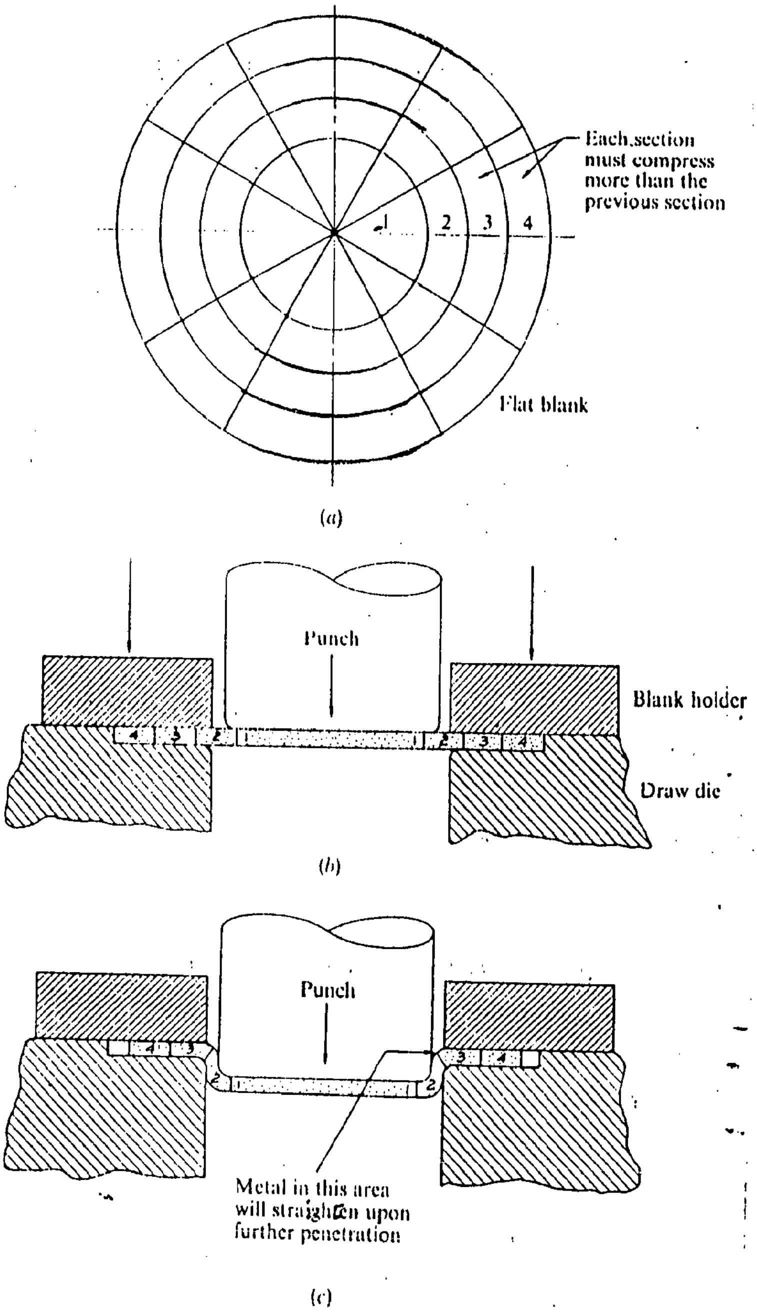


Fig. 2.20 Metal flow during drawing

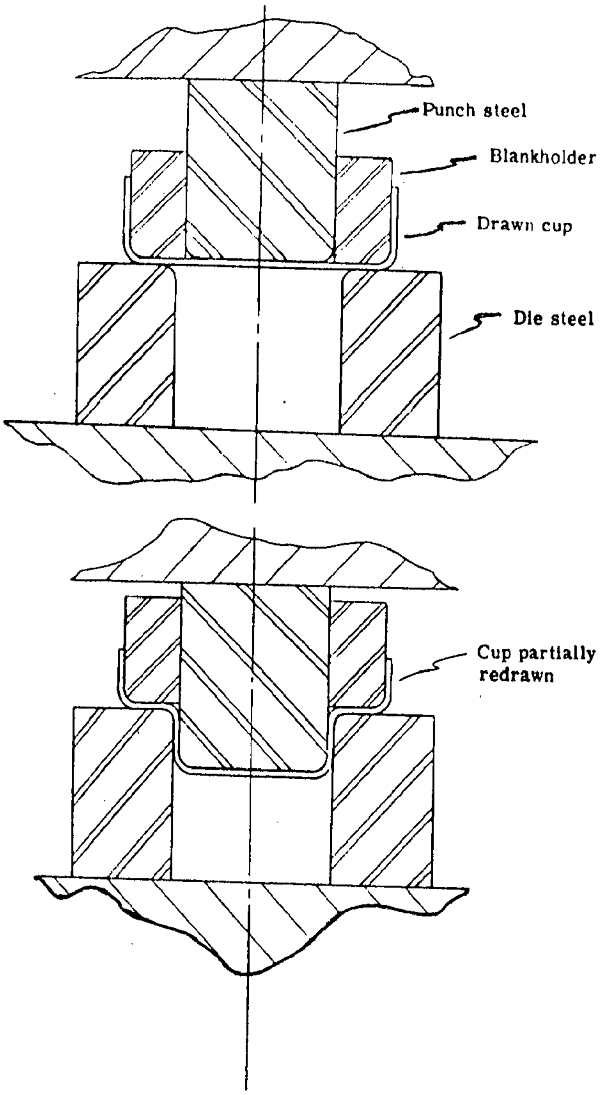


Figure 2.21 Redrawing of Cups

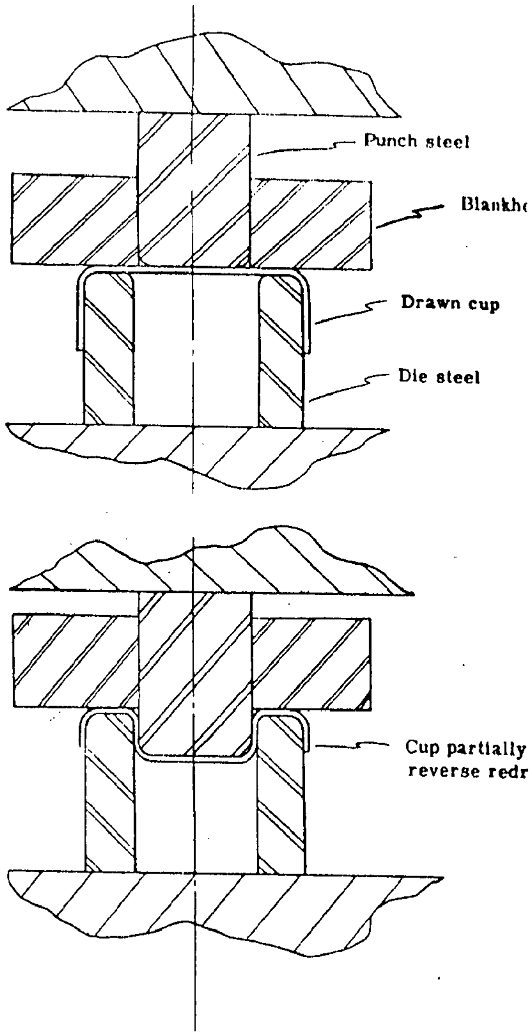


Figure 2.22 Reverse Redrawing of a Cup

CHAPTER - 3

LITERATURE REVIEW

Extensive research has been done to study the effect of various factors on sheet metal operations. This study is primarily concerned with the research work related to effects of metal properties before press working operations, geometrical properties desired on the sheet metal part and sequence of operations.

3.1.EFFECT OF METAL PROPERTIES ON PRESS WORKING OPERATIONS

P.B. Mellor [7], studied the effect of anisotropy on plastic deformation in sheet metal forming. He found Hill's theory to be better suited to describe the effect of anisotropy on yield criterion for plane stress situation, but still within theoretical limits. **Kurt Lange and Han Wilhelan [8]** discussed the role of the various interacting factors in forming operations, namely the effect of various metal properties such as yield strength, ductility, grain-orientation etc. on sheet metal blanking (or piercing) and forming operations. Forming limit diagrams for stretching and drawing of sheet metal were considered with the veiw to explain their general shape by **M.C. Shaw and J.P. Avery [9]**. They found that the best approach to develop sheet metal forming limit diagrams based on the first visible appearance of instability, is an empirical one and test procedure is also suggested.

Bradley Dodd and Peter Hartley [15] suggested the inclusion of process simulation in forming CAD/CAM systems, along with an assessment of damage accumulation in the form of an appropriate workability criterion. They reviewed workability with regard to ductile-fracture criteria in detail. Principle conclusions of the analyses show that plastic work and hydrostatic stress are important parameters to use in ductile-fracture prediction.

The effect of anisotropy on pure bending of sheet metals was studied by **Z. Tan, et. al. [21].** A constant specifying the plane bending of anisotropic sheets was defined and incorporated in the two models developed in their work. Model I describes the bending process in which Bauschinger effect is absent while model II describes maximum strain softening on reverse straining. Material thinning in bending was found to occur mainly due to effects of Bauschinger and strain hardening. The effect of anisotropy on material thinning of a bend is small but has a large effect on bending moment. Bending moment also increases with the bending curvature (k) because of strain hardening.

Forming limit curves were simulated by **L.S. Toth et al. [24]** using a Marciniak-Kuczynski type initial defect theory. The technique was generalised to account for the texture development during deformation. Three initial texture characteristics for aluminium were selected to study the effect of initial textures as well as their development on the forming limits. It was found that both the initial texture and their subsequent development have important influence on limit strains. Evolution of anisotropy decreases formability and also equalizes the forming limit curves.

Z. Tan et al [20] proposed a new method for evaluating distribution of residual stresses in bent sheet metals. Due to non-uniform distribution of strain and stress across thickness, spring back on unloading induces residual stresses in a bent specimen. The authors established that spring back and residual stress can be expressed as a function of geometric parameters and material thickness eg. bending, curvature, thickness, Young's modulus, work-hardening index etc. The layer removing method was used to determine the residual stress in the study.

A sequential design procedure to optimize sheet forming processes was developed by **K. Chung et. al.[26]** utilising forming design theory, FEM analysis and experimental trials. For demonstration purpose, this procedure was used to design a blank shape for a highly anisotropic aluminium alloy sheet (2090-73) that results in a deep-drawn, circular cup with minimal earing. All blank shape design methods require a certain number of iterations. However, the sequential procedure can be more effective than the other iterative methods based on FEM analysis in conjunction with experimental trials or experimental trail alone.

3.2. EFFECT OF GEOMETRICAL FEATURES ON PRESS WORKING OPERATIO

Amy J.C. Trappey and C.-S Lai [22] proposed a unique process driven, feature- hierarchical data representation scheme. A scheme for sheet metal parts was developed so that designers could use the process related feature hierarchy to describe them and at the same time, express design intention and tolerances. Features were classified into two types, Master feature to represent primary profile of sheet metal parts and Manufacturing feature to represent a single sheet metal manufacturing process. Geometric and dimensional tolerance information can also be added to feature definition to make the sheet metal part design ready for further processing, assembly, inspection etc. Topology, geometry and tolerance data are considered for the scheme of data structure. A prototype system called SMCAD is implemented to demonstrate the sheet metal design scheme.

A classified system for shearing operations is presented by **R. Jagirdar et. al. [23]** who also developed the concepts for extracting entity groups, recognizing them and characterising shearing features for sheet metal components in two dimensional layout. Featured are recognized by studying the wire frame representation of the layout and a set of principles are derived to relate the features geometrically and topologically. Features which form potential candidates for CAPP system are also determined by this system. This helps in development of many alternative process plans in general and selection of an optimum process plan based on constraints in particular.

Raj Radhakrishnan et al. [25] proposed a set of algorithms for detecting design violations in sheet metal components. Violations occur when holes, slots or other features are too close to one another. As the contour of parts becomes complicated and the number of features on the sheet metal part increases, it becomes difficult to check the rules exhaustively because of the possibility of combinatorial explosion. The algorithm presented by them uses medical axis transformation to decompose a given domain, thus preventing a combinatorial explosion and also provide a means to integrate the rule checker with a design advisor.

A methodology for automatic extraction of manufacturable features from engineering drawing created in CADD format was proposed by **B.S. Prabhu and S.S. Pande [30]**. This employs the techniques of string based pattern recognition and natural language processing. Drawing entities are processed to derive feature string patterns, which are then syntactically analyzed to detect the feature topology and geometry. These informations are further augmented by non-geometric data like dimension, position, tolerances and relevant drawing callouts. The proposed system is capable of selecting generic classes of features like holes, pockets, steps, slots, bosses etc.

3.3. SEQUENCE OF OPERATIONS

R.Van Hasselt and W.J. Ondolf [8] developed a standard work plan for simple sheet components which could be categorised into a single manufacturing group.

A Raggen bass and J. Reissner [12,16] developed an expert system which recognizes part geometry and generates NC manufacturing plan containing only stamping operations, only laser operations or a stamping-laser combination. The expert system described in their work constitutes the link between the CAD drawing of a sheet part and its manufacture (Fig.[3.4]). Various modules of the expert system are shown in the Fig.[3.5]. The main features of the expert system are an algorithm for tool selection, the formulation and consideration of tool loading rules and a fast algorithm for path optimization.

An expert system for forming sequence has been designed by **A. Azushima and M. Kim [13]** for cold forging of axisymmetric solid parts. In this system, the dimensions of intermediate work piece at successive stages are determined by geometrical rules, if the shape and dimensions of the final product are provided.

Jeffrey S. Smith et al.[17] described a relational data base system for semi generative process planning for sheet metal parts. The system integrates a feature based relational database for the parts, a forward chaining rule-based strategy for machine selection, both global and feature-specific execution of the rules and a graph theoretic cost optimization for optimal process plan selection. They preferred to generate holes near bend or edges (or those requiring careful) by machining operations instead of shearing operations. Besides, the following sequence of operations was suggested for generating the features in any part.

(1) generate periphery

(2) generate pre-bend holes (using metals cutting operations)

(3) generate pre-bend slots (metals cutting operations)

(4) generate bends

(5) generate post-bend holes (Using machining operations)

(6) generate post-bend slots (Using machining operations)

D.E. Hardt et al. [18] worked to develop a process model for use in simulation of manufacturing of cylindrical shapes from plate, to provide design sensitivity information, and to explore the potential for improved process control. The process is modeled as a series of overlapping two -dimensional three-point bends, where the overlap includes the plastic zone from previous bends. The deformed zone is modeled both as a non-flat initial geometry for the next bend and as a locally strain-hardened material with residual stresses. A series of experiments were performed on plates of steel, aluminium and brass to examine the accuracy of the model and a good agreement was found after adjusting assumed parameters. Results show that prior bending history has a marked effect on the basic process resolution and therefore on the effective precision and sensitivity of the process.

Sheet metal fabrication on NC turret punch press is accomplished by first punching the desired holes in the parts nested on sheet stock followed by nibbling the boundaries of the parts in order to separate them from the sheet. **D.Veeramani and S. Kumar [27]** have addressed the problem of minimization of the total time taken for the nibbling operation for a given sheet configuration of nested parts. The authors have presented two approaches, namely the Coupled and Hierarchical heuristic, to optimise the nibbling operation and discuss their performance on sample data sets. Of these, the coupled heuristic is not only rapid, but also yields a solution quality close to that obtained by other heuristics. Incorporation of this heuristic was therefore suggested within CAD/CAM systems for sheet metal fabrication for more effective utilization of NC turret punch presses.

E.Cuesta, et al. [28] have proposed a detailed time and cost analysis for process planning of sheet-metal operations. A special computer module for determining the time and cost in sheet metal operations has been developed and integrated in a CAD/CAM system which incorporates modules for nesting, tool path generation, post processing etc. A special module allows all the geometrical and technological data from other modules in the CAD/CAM system required for the cost and time analysis to be automatically included without the need to manually enter the data in the module. The cost and time considerations also help to determine an optimal plan from among the various plans available.

Joseph A. Svesta, et. al. [11] worked to suggest an improvement in the productivity of a class of NC punch presses which operate from either an off-line computer control or under direct numerical control. The problem of tool selection and table motion during the manufacture of a product by punching an array of holes in a sheet metal with a sequence of tools of various shapes and sizes is formulated as a Travelling Salesman Problem (TSP). Two TSP heuristics, one old and one proposed by authors, named GIL, were employed in a comparison test with NC press manufacturer's heuristic. Both the TSP heuristics out performed the manufacturer's heuristic by 10% of more. Later, **Joseph A. Svestka [14]** formally treated the problem of how to impose precedence constraints on the sequences by partitioning the problem into a number of smaller problems and patching them together to satisfy the constraints, or by direct construction of such, usually involving the Closest Unvisited City (CUC) heuristic. However, such heuristics have some difficulties, for instance, CUC can fail to generate a feasible solution for such problems even though solutions can be shown to exist. The author therefore introduced a new method by modifying the old proposed GIL heuristic for imposing precedence constraints, which either finds a feasible solution or shows that there are none

S.V. Bhaskarareddy et al. [29] demonstrated the use of genetic algorithm as a global search technique for a quick identification of optimal or near optimal operation sequences in a dynamic planning environment. A novel initialization scheme for representing the genetic code and a new cross over operator were designed to retain the local operation precedence for each form feature. Various manufacturing constraints considered in the study pertain to :

(a) accessibility
(b) non-destruction, together called preconditions.
(c) locations and
(d) datum holding or geometric tolerance.

The proposed heuristic obtains quick solution requiring about 10-40 sec. As the computation time taken to generate the feasible sequences is low, the software can be run several times to facilitate the process planner in obtaining alternative operation sequences, thereby generating alternative process plans.

J.R. Duflou et al. [31] proposed a methodology, involving branch -and -bound techniques to evolve the possible sequences for bending operations. The reported branch-and -bound search method is characterized by a dynamically updated penalty system that reflects the manufacturing knowledge obtained through analysis of partial sequences.

3.4 PROPOSED WORK

The research work carried out till now throws light on the effects of various parameters on pressworking operations. However, there are few investigations aimed at determining the sequence in which operations of a particular type should be carried out to produce the desired featrures on a sheet metal part. Some attempt has been made to determine the sequence of operations for two or three different operation types, but that too, by either considering a single parameter or taking a group of similar components.

In general, there seems to be a gap in research which aims to determine the operations sequences while considering multiple operation types and more general type of products.

In the present thesis an effort has been made to bridge this gap by developing a methodology for determining operation sequences for different components involving multiple operation types and taking into consideration the geometrical features and tolerances desired on the component.

These operation sequences generated are evaluated for tool setup changes and machines changes required and the time used for producing a part. Based on these criteria, the sequences can be accorded a priority rating as a recommendation to the user.

CHAPTER - 4

PLAN FOR GENERATION AND EVALUATION OF OPERATION SEQUENCE

This chapter deals with the proposed methodology for obtaining and evaluating the operation sequences of press working operation on sheet metal parts. The basic approach used for generating the sequence for developing the desired features and the various assumptions made are also discussed.

4.1 DETERMINATION OF BLANK SHAPE AND SIZE

It is assumed that the outer blank shape and size would be an input for the problem. Among the infinite number of possible shapes, the circular and polygonal shapes of blank are considered.

For a circular blank, following parameters should be given as input :

* co -ordinates for the centre of circle w.r.t. any reference

* radius of circle.

For proper dimensioning of various features and their location, a reference point should be initialized w.r.t. which the co-ordinates of all the features can be given .

For a circular blank this reference can be determined as

$$x_r = x_o - \text{radius}$$

$$y_r = y_0 - \text{radius} \qquad (4.1.1)$$

where,

x_0, y_o = center co-ordinates of blank w.r.t user's reference.

The reference axes are then the vertical and horizontal lines passing through (x_r, y_r), as has been depicted by dashed lines, in Fig. [4.1]

For polygonal shape of blank, the following parameters are required as input :

* number of edges in the polygon, which is equal to the number of corners.

* co -ordinates of corners in the polygon w.r.t any reference.

For polygonal blank, we can locate the reference as the minimum of all the x and y-coordinates, i.e.

$$y_r = \min (x_i)$$

$$y_r = \min (y_i) \qquad (4.1.2)$$

where,

$i = 1,2,3, \ldots$ no. of corners

The reference axes can consequently be determined as shown in the Fig.[4.2]

The other dimension which should be specified is the thickness of sheet metal. Fig. [4.3]

4.2 DETERMINATION OF FEATURES TO BE GENERATED ON THE SHEET METAL BLANK

Corresponding to the broad classification done for the press working operations, the features can be classified into the following three types.

(a) shearing features

(b) forming features

(c) drawing features

From among the various features discussed in the previous chapters, those considered for the generation of operation sequence are discussed.

4.2.1 Shearing Features

From the various shearing operations discussed for developing shearing features, the commonly used punching, slotting and perforating operations used for producing holes and slots are considered. If dimensions of holes or slots are small and they are more in numbers, they are called perforations.

If there are two or more holes or slots of equal dimensions, they can be grouped together.This helps to reduce the number of dimensional input.

Hole

For dimensioning a hole only the radius of hole needs to be given Fig.[4.4], while for locating the hole w.r.t. to the reference axes, the co-ordinates of the centre of circle need to be specified Fig.[4.5].

Slot

Three common types of slots have been considered

* oval

* rectangular

* square

For specifying a slot, two dimensions are required (except for square slot)

* Major dimension, (m_a), mm

* Minor dimension, (m_i), mm

These are shown in the Fig.[4.6]

For Rectangular Slots, the co-ordinates of any one edge and the other dimension should be specified. For a square slot, the co-ordinates of any one edge are sufficient. The dimension of a given edge can be determined by the distance formula. For example if co-ordinates (x_1, y_1) and (x_2, y_2) are given then the edge dimension is

$$m_a = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2} \qquad \ldots(4.2.1)$$

For an oval slot, the co-ordinates of any of two straight edges and the minor dimension need to be given. Using these, we can determine major dimension and radius as

$$m_a = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2} + m_i$$

$$r_s = \frac{m_i}{2} \qquad \ldots(4.2.2)$$

Using the two dimensions and the co-ordinates of any one edge, the coordinates of the other edge can be determined by the following equations.

$$y' = \frac{p\sqrt{1+m^2} + m^2c_1+c}{(1+m^2)}$$

$$x' = m(c_1 - y') \qquad \ldots(4.2.3)$$

where,

$y' = y_3, y_4$

$x' = x_3, x_4$

m = Slope of edge $= \frac{y_2-y_1}{x_2-x_1}$

c = Intercept of edge on the y-axis

$= y - mx$

$$[y = y_1, y_2$$

$$x = x_1, x_2]$$

$$c_1 = \frac{my+x}{m}$$

4.2.2 Forming Features

The different forming features considered are

- * bend
- * flange
- * hem

As in the shearing features, we can also group the forming features having similar properties.

Bend

A bend can be any of the three type

- * V-bend
- * U-bend
- * Wiped-bend

These are shown in the Fig.[4.7], along with the parameters required for their definition.

where,

α_b = angle of bend, degree

r = radius of bend, mm

l_b = bend length, mm

p_2 = distance between U-bend line

The input required is the radius. For V-bend angle (α_b) is additionally specified as it is a bend geometery variable. Bend length can then be determined by he following equation

$$l_b = \frac{\pi}{180} \times (r + 0.4\ t) \times \alpha_b \qquad ...(4.2.4)$$

where,

t = thickness of sheet, mm

For the purpose of location of bend line, the coordinates of end-points of bend line should be given. Using these, the equation of the bend line can be written in the standard form

$$a_1\ x - y + c = 0 \qquad ...(4.2.5)$$

where,

a_1 = slope of bend line

c = intercept of bend line on y-axis.

For the U-bend, the other bend line can be determined by the procedure similar to that used for determining the other edge of the slot.

Flange.

This is very much similar to a bend, except that the portion of sheet formed up (or down) is small in relation to the remainder of the part Fig. [4.8]

α_f = angle of flange. degree

r_f = radius of flange, mm

l_f = flange length, mm

Given the angle and radius of flange as inputs, the flange length can be determined as follows

$l_f = \frac{\pi}{180} \times (r_f + 0.4\ t) \times \alpha_f$ ...(4.2.6)

where,

t = thickness of sheet, mm

For locating the flange line, again the end co-ordinates of the flange line need to be specified.Using these co-ordinates, the equation of the line can be generated in standard form as :

$a_1x - y + c = 0$ ...(4.2.7)

Where,

a_1 = slope of flange line

c = intercept of flange line on reference y - axis.

Hem

A hem is shown in the Fig.[4.9]. To specify a hem we need to know the plane in which it is made, i.e. above or below the plane of blank.

Besides, the location of Hem line needs to be specified by giving the co-ordinates of the end point. Using these, the equation can be generated in standard form as

$a_1x - y - c = 0$ ...(4.2.8)

4.2.3 Drawing Features

Among the drawing features, Cup Draw and Box Draw have been considered.

Depending on the type of die used, the draw may be

* single action draw

* double action draw

In single action draw, die has no blank holder, while a double action draw die uses a blank holder. For thick metal, blank holder is often not necessary.

The common dimensions required for both type of draw are

* bottom curve radius , r_{bo}, mm

* draw height, h, mm

Cup Draw

For location and dimension of a cup draw we need,

* centre co-ordinates of cup draw (x_1, y_1)

* diameter of the bottom circular portion, d, mm

Using these, the blank diameter required can be calculated as

$$D = [(d + a)^2 + 4 \times d\,(h - 0.43 \times r_{bo} - 0.43\, r_f)]^{1/2} \qquad \ldots(4.2.9)$$

where,

a = Length of flange portion on the draw, mm

Box Draw

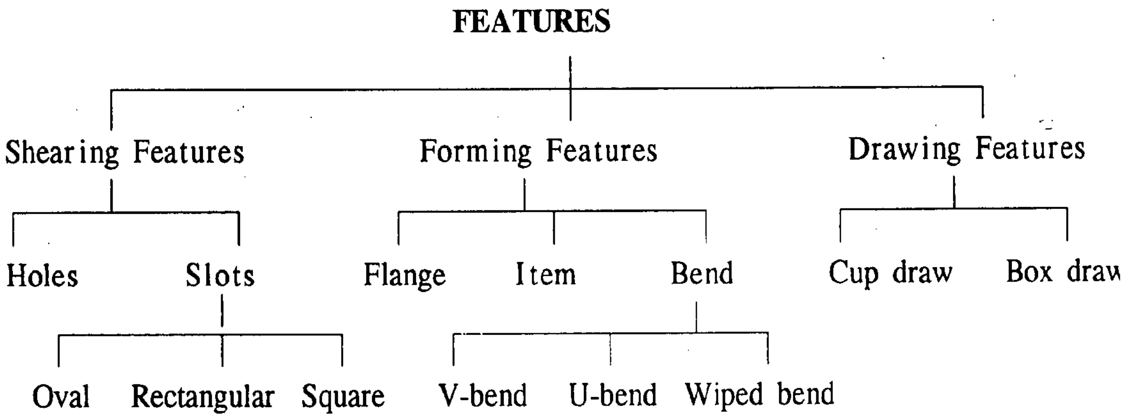
A box draw is assumed to be either horizontal or vertical w.r.t. the horizontal axis. So for location of a box draw, if the co-ordinates of any of the bottom line are given and the distance between parallel lines is also known, the other draw lines can be determined easily using the bottom radius (r_{bo}) and draw height (h)

The decision regarding redraw can be taken, by making use of the following table.

TABLE 4.2.1

t/D x 100		Percent Reduction of First Draw $\frac{D-d}{D}$ x 100
Single Action Die	Double Action Die	
1.2	0.15	30.0
	0.20	35.0
	0.30	40.0
2.0	0.40	45.0
2.5	0.50	47.5

The following chart [C-4.2.1] summarizes overall the different type of features considered.



C-4.2.1. Various Features Considered

4.3 GENERATION OF PRECEDANCE BETWEEN FEATURES

For determination of operation sequences some precedances should be established between various features that are to be generated. These precedence are set in order to properly achieve the required specifications of the features and to reduce the number of tool setups.

4.3.1 Guidelines for Precedance

Several guidelines, which can be helpful for laying precedance among features [2,6,23] are discussed below.

(i) Intra feature rules

Are those rules, that involve a single feature only. These rules give critical dimensions to the parameters of the feature.

Holes and slots

Minimum diameter of the hole should be D(min) = t or 0.04 inch, which ever is greater Fig.[4.11].

Same rule applies to slots with minor modification, i.e., of substituting minor dimension instead of the diameter in the hole.

Bends

Minimum bend radius should be R(min) = 1.5 t so as to avoid cracks on the external surface of the bend due to high tensile stress.

(ii) Inter feature rules :

They describe the relationship between features, or between features and the part contours, ie, edges of the blank. Features may be of the same type (eg. two holes) or different (eg. a hole and a dimple).

A few of these are :

- In order to avoid distortion of the edge of the part, the holes should have a minimum distance from the edge.
- Similarly to avoid distortion of holes (or slots), they should have certain minimum distance between them Fig.[4.12].
- In order to prevent the distortion of punched holes during bending a minimum distance should be maintained from the bend, which is a function of material thickness and bend radius Fig.[4.13].

(iii) Generic Rules

Based on the basic principles, a few generic rules are also developed. These rules are not complete in themselves in the sense that when applied to features, they require the features to be explicitly recognised before hand. A few of these rules are tabulated as below.

Table 4.3.1 Generic Rules

Edge 1	Edge 2	Minimum Distance
Form	Bend	$10t + r_1 + r_2$
	Form	$4t+r_1+r_2$
	External edge	$4t+r_1$
	Hole	$3t+r_1$
Bend	Bend	
	External edge	$2t+r_1$
	Hole	$2t+r_1$
External edge	Hole	$t<0.032$in, 0.060 in $0.032<t<0.125$in, 2t $t>0.125$in, 2.5t
Hole	Hole	$t<0.032$in, 0.060 in $0.032<t<0.125$in, 2t $t>0.125$in, 2.5t

Sequence of operations

Sequence of operations may be varied in some cases, at other times, the sequence is limited. Certain operations must follow others. For some parts more than one sequence may be used successfully to manufacture the part, although such liberal variations in operation sequence is not always practical or possible. In some instances, the specifications on the part print require that a certain sequence be used. Several guidelines to be followed while determining operation sequence are discussed now [2,6,23].

Punching Slotting and Perforating

1. Holes near the edge of the part should be cut after blanking. The cutting action during blanking might distort the hole.
2. When large and small holes are located close to each other the large hole should be cut first. The cutting action during cutting of the large hole might distort the small hole.
3. When a hole is located near the radius of a formed part, the hole should be cut after forming. Forming might distort the hole.
4. When a hole is located in an area that is wiped, burnished, or ironed by the forming steels, the hole should be cut after forming to prevent distortion of the hole.
5. Holes in drawn parts must be cut after drawing. Holes in high stress areas would cause failure of the metal. Also, the holes would be distorted severely.
6. Whenever possible, holes should be cut when the part is flat. After forming, or drawing expensive cam might be required or the part might have to be tipped to an awkward angle. In either case, die cost would be

higher.

7. Holes should be cut after forming or drawing when close tolerance on hole location must be maintained. Predicting hole location before forming or drawing would give only an approximate location.
8. When several holes are cut in the flange or bottom of a cup, they should be cut simultaneously, if possible. Otherwise, a second die with gages in the first holes would be necessary, and maintenance of close tolerance on hole location would be difficult.

Drawing, Flanging Hemming and Bending

1. Drawn parts must be flanged after the drawing operation. Flanging during the drawing operation would prevent metal flow and wrinkles would occur in the flange because no blank holding pressure could be applied there. The same is true for hemming.
2. The part edge is first flanged and then the flange is further formed over to obtain the hem. Forming a hem in one operation generally requires the use of expensive cams.
3. It is generally more efficient to flange first and bend the part afterwards.
4. Within bending operations, the bends with smaller angle of bend should be bent later.

Limitations listed above control the sequence of operations for many sheet metal parts. Other more special limitations may occur, but the listed ones are the most common.

For proper generation of precedance between any two features, calculation of distance between them is essential, because if distance is small, the strain developed during generation of one feature can cause some degree of changes in dimensions of the other.

4.3.2 Precedance Among forming features

During forming operations, the sheet metal is exposed to stresses greater than yield stress, which helps the metal to be formed plastically. This metal flow has its effect upto a certain distance, depending up the sheet thickness and material [6]. Therefore, if the distance between forming features is small, the dimensions of the existing features may change during forming of other features.

For mild steel sheets the minimum distance between forming features upto which the effect of strain is negligible is [23] [Fig. 4.14].

$$dt_{min} = 4t + r_1 + r_2 \qquad \text{...(4.3.1)}$$

and the minimum tolerance that can be achieved is

$$Tol_{min} = \pm\ 0.38 \text{ mm.} \qquad \text{...(4.3.2)}$$

where,

t = thickness of sheet, mm

r_1 , r_2 = radius of formed features, mm [For hem $r = 0$]

Among the features required to be formed on the sheet, the distance of mutually parallel features should be calculated and checked.

Say there are two formed features (bend, flange or Hem) parallel to each other and defined by corresponding forming lines (along which forming is done). The distance dt_o', between the forming lines is

$$dt_o' = \left\| \frac{c_1 - c_2}{(a_1^2 + b_1^2)^{1/2}} \right\| \qquad \ldots(4.3.3)$$

while, the actual, unaffected distance 'dt' can be calculated by deducting the form length of features [bend length for bend and flange length for flange]

$$dt = dt' - \left(\frac{l_1 + l_2}{2} \right) \qquad \ldots(4.3.4)$$

where,

l_1, l_2 = form lengths, mm

a_1, b_1 = coefficients of x and y in the equation of form lines.

The precedance among forming features are generated based on calculation of distances, the tolerance specified and the suggested precedance rules.

For example,

* a flange should preceed bend formation

* hemming should follow flanging

4.3.3 Precedance between shearing and forming features

Shearing operation basically involves the cutting of an edge in the sheet. If this edge is close to formed features, it will cause deformation of edge during forming. It is further suggested that, as far as possible, the shearing operations should be done when the part is flat. It therefore follows that the distance of shearing features (holes and slots considered here) should be calculated to determine the precedence.

Minimum distance of an edge of a hole or slot from any formed feature is

$$dt_{min} = 2t + r \qquad \ldots(4.3.5)$$

and the minimum tolerance that can be achieved on the dimensional location of holes/slots is

$$\mathrm{Tol}_{min} = \pm\, 0.25 \text{ mm} \qquad \ldots(4.3.6)$$

where,

t = thickness of sheet, mm

r = radius of formed feature, mm

Hole

The distance of a hole from a form line can be calculated as in Fig. [4.15].

$$dt'_i = \left\| \frac{a_i x_n + b_i y_n + c_i}{(a_i^2 + b_i^2)^{1/2}} \right\| - r_h$$

where,

$i = 1,2,\ldots, n$

n = number of formed features with equal dimensions.

a_i, b_i = coefficients of x and y in the equation of form lines.

The unaffected distance, (d_1 or d_2) is calculated by subtracting the form length.

$$dt_i = dt'_i - l/2 \qquad \ldots(4.3.8)$$

where,

l = form length, mm

and the distance of a hole from the same type of formed features (with equal dimensions) is then

$$dt = \min\,(di)$$

Distance of a slot from a formed feature can be calculated depending on the orientation of slot w.r.t the form line

- * parallel
- * perpendicular
- * inclined

$$dt' = \left\| \frac{a_1 x_{1s} + b_1 y_{1s} + c_1}{(a_1^2 + b_1^2)^{1/2}} \right\| - m_i/2$$

for parallel slot.

$$dt' = \left\| \frac{a_1 x_{2s} + b_1 y_{2s} + c_1}{(a_1^2 + b_1^2)^{1/2}} \right\| - m_a/2$$

for perpendicular slot

dt′ = distance of closest corner, for inclined slot.

$$= \left\| \frac{a_1 x'_{4s} + b_1 y'_{4s} + c_1}{(a_1^2 + b_1^2)^{1/2}} \right\| - m_a/2$$

for inclined oval slot.

where,

m_a = major dimension of slot, mm

m_i = minor dimension of slot, mm

x_{is}, y_{is} = center co-ordinates of slot.

x'_{4s},y'_{4s}= center of are of oval slot.

and the actual distance can be calculated by deducting the form length.

$$dt = dt' - l/2 \qquad (4.3.10)$$

where

l =form length, mm

As for the holes, the distance from one class of formed feature (with equal dimension) is the minimum of all distances from those features.

If the distance calculated is less than the minimum required and the tolerance specified for this hole or slot is also less, then the hole or slot should be made after the formed feature considered, otherwise the shearing operation should be done before forming as far as possible.

4.3.4 Precedance within Shearing Features

As shown in the Fig [4.12], minimum distance between shearing features up to which the dimensions remain unaffected is a function of thickness of sheet metal. And the minimum tolerance that can be achieved is ±0.25 mm. So the distance should be calculated between shearing features, to generate precedence among shearing features.

For a hole

The following equation is used to calculate the distance of one hole from the other Fig. [4.17].

$$h.h = [\,(x_{h1} - x_{h2})^2 + (y_{h1} - y_{h2})^2]^{1/2} - r_{h1} - r_{h2}. \qquad ...(4.3.11)$$

where,

x_{hi}, y_{hi} = center co-ordinates of holes

r_{hi} = radius of holes, mm

To determine distance from a slot, the distances along the slot axis [h.sl-ax] and perpendicular to it (h.sl-per) should be first calculated

$$\text{h.sl - ax} = \text{c.c. x } \cos\alpha - r_{h_1} - \frac{m_a}{2}$$

$$\text{h.sl - per} = \text{c.c. x } \sin\alpha - r_{h_1} - \frac{m_i}{2} \qquad \text{...(4.3.12)}$$

where

m_a = major slot dimension, mm

m_i = minor slot dimension , mm

c.c = center to center distance

$= [(x_{h1} - x_s)^2 + (y_{h1} - y_s)^2]^{1/2}$

If, h.sl-ax $<$ m_a, h.sl = h.sl - per

or h.sl-per $<$ m_i, h-sl = h.sl - ax

But if, h.sl - ax $\geq$ m_a

and h.sl - per $\geq$ m_i

then h.sl = max (h.sl-ax, h.sl-per) ...(4.3.13)

For a slot

Only the distance between parallel and perpendicular slots can be calculated. Here again, the distance along the axis (sl.sl-ax) and perpendicular to it (sl.sl-per) should be calculated Fig. [4.18].

$$\text{sl.sl-ax} = \text{c.c}_2 \text{ x } \cos\alpha_2 - \frac{(m_{a1} + m_{a2})}{2} \text{ , for parallel slots}$$

$$= \text{c.c}_3 \text{ x } \cos\alpha_3 - \frac{(m_{i1} + m_{i3})}{2} \text{ , for perpendicular slots}$$

$$\text{sl.sl-per} = \text{c.c}_2 \text{ x } \sin\alpha_2 - \frac{(m_{i1} + m_{i2})}{2}, \text{ for parallel slots}$$

$$= \text{c.c}_3 \text{x} \sin\alpha - \frac{(m_{i1} + m_{a3})}{2} \text{ for perpendicular slot} \qquad ...(4.3.14)$$

where,

c.c = centre to center distance

if sl.sl.-ax$<$ma, then sl-sl = sl-sl-per

or sl.sl-per$<$mi, then sl.sl. = sl.sl-ax

and if not, then

sl.sl. = max (sl.sl-ax, sl.sl-per) ...(4.3.15)

Distance of a sheared feature form a group of sheared features is the minimum of its distances from all the features in that group. If this distance comes out to be less then the minimum specified for shearing features and the tolerance is also less than the minimum achievable, then it is generally advised that the shearing feature with the smaller dimension should follow the shearing feature with larger dimension.

4.3.5 Precedance Relation of Drawing with Other Features

Drawing operation should be done on the sheet metal initially, because the metal flow involved in this operation is quite significant [3]. This may affect the dimension of the pre-existing features, if they are present.

Hence, draw features should be given precedance over other features, except for holes or slots, which are significantly far from the drawn features.

4.4 GENERATION OF FEASIBLE OPERATION SEQUENCES

The precedence among various features is determined as described in. the previous section. These precedence can be codified and put in a two-dimensional matrix, called the feature relationship matrix Fij [ ]. The value of each element in the feature relationship matrix is codified '0' or '1', based on the following relationships.

fij = 0, if feature 'i' has no relation with feature 'j'

fij = 1, if feature 'i' can not be made unless feature 'j' has been made.

= or when 'i' is equal to 'j'

Construction on this matrix follows the guidelines summarized in the preceding section. Additionally the distances between and the tolerances required on the features are calculated to serve as inputs for the matrix generation.

Operations to generate 'n' features can be arranged in n! ways so that there are n! operation sequences to produce the given part. All these n! operation sequences may not be technologically feasible. The technologically feasible operation sequences from among the total n! sequences are selected by making use of the feature relationship matrix.

For example, if fij = 1, then those sequences where 'i' occurs in the sequence before 'j' will be rejected as infeasible, while those where 'j' occurs before 'i' will only be selected. The check for infeasibility is done with the help of an interactive computer program module which iteratively checks this relationship among different operations and rejects the infeasible ones.

The process engineer can now select the best sequence according to the evaluation criteria adopted.

4.5 EVALUATION OF OPERATION SEQUENCES

To assist the user in selection of an appropriate operation sequence, the feasible operation sequences are evaluated based on the following three criteria :

(a) tool set up changes (die changes).

(b) machine changes.

(c) manufacturing time of the part.

4.5.1 Tool Setup Changes

In pressworking operations, tool setup refers to an assembled die. The pressworking die essentially consists of two halves the punch half (attached to the ram) and the die half (attached to the bed). The punch half includes punch shoe, guide pin bushings and punch or die steels. The die half includes the die shoe, guide pins and punch or die steels. Other accessories may be attached as required by the type of operations or component geometry.

The tool setup or die changes will be required in several cases, viz.,

(a) when a subsequent feature is different, though it is essentially in the same operation group. (For example, if a V-bend follows a U-bend or slotting is done after hole punching, a tool change is required notwithstanding the fact that the conceived operations belong to the same group).

(b) when the features are of the same type but their dimensions are different. (For example, radius of hole, or the major or minor dimension of slot may be different).

4.5.2 Machine Changes

When any subsequent operation falls in to a different operation group, the press working machine should be changed, so as to avoid over loading on the same machine, even if same machine type is required. Hence, press working machines for different types of operations are assumed to be different. For shearing operations and forming operations mechanical presses, actuated by cam are considered. While for drawing operations, hydraulic presses are assumed to be in operation.

4.5.3 Manufacturing Time of the Part

Manufacturing time for a component can be defined as the time required to produce the component. It includes the following time elements :

* non-productive time elements

* press working time elements

These elements are discussed below.

4.5.3.1 Non-Productive Time Elements

In pressworking operations, the major non-productive time elements are :

- tool changing time
- machine changing time
- work reorientation time

TOOL CHANGING TIME

Change of tool setup is required in two cases, (Section 4.5.1) and contributes to non-productive time of the component. Here, one assumption has been made that tool change procedure involves removal of the existing die from the machine and attachment of another, pre-assembled die to the bolster plate of pressworking machine. It is further assumed that locators and clamps have been provided on the machine to help in quick changeover.

To estimate the time required, the above steps in tool changeover have been further broken into elementary sub steps, such that the time of each substep can either be taken from standard time data or calculated applying certain recommended norms. The substeps are :

1. moving arm to tool stand for wrench and grasping it.
2. moving arm with wrench to the first clamp.
3. disengaging the clamp nuts of the four clamps each on the die half and the punch half.
4. movement between the clamps.
5. movement of both arms to the die and picking it from its seat.
6. movement of die to its stand and releasing it there.
7. picking the other die from its stand and moving it to the pressworking machine bed.
8. engaging the clamps on the die.

Assumptions have been made for the distance travelled by the arms, (for example, the distance travelled to reach the wrench is assumed to be 30 inches and that for the first clamp is 35 inches. While distance between the two dies on their stands is assumed to be 20 inches). These assumptions are made on the basis of simulation of operator's body motions.

Inter clamp distances on the die are taken from the die-data tables [1], using the press tonnage and bolster plate dimensions as the selection factors.

The tool changeover time is calculated by adding up all the above time elements by taking their values from the data base[7]. On this an allowance of

40% is allowed as relaxation allowance, fatigue allowance, contingency allowance etc.

MACHINE CHANGING TIME

When the type of operation required on the component changes, the pressworking machine needs to the changed. This involves removal of the component from the previous machine, its transfer to the other machine and finally clamping it on that machine. Machines are assumed to arranged in the layout as depicted in Fig 4.19.

Here, the dimensions of bolster plate are taken from standard die data[1] based on press tonnage. The press tonnage is calculated using the force formulae, as discussed in chapter 2, by taking a factor of safety of 5.

The following steps are planned for machine changing in the present work:

(a) approach the clamps and grasp them.

(b) disengage the two clamps.

(c) unseat the work.

(d) move back the work.

(e) walk with the job to the other machine (in steps of 30 inches).

(f) reach the location of work.

(g) align and sea the work.

(h) reach for the clamps and engage them.

(i) move away the arms.

Distances travelled are calculated using the dimensions of bolster plate as in Fig 4.19 and the time taken for each substep is determined using the standard tables[7]. These time elements are enhanced by 40% to determine the machine changing time.

WORK REORIENTATION TIME

In the events when a similar feature is to be made at different locations,and which cannot be made at one time, the component needs to be oriented after each operation to bring the part position in front of the punch where the feature can be made. This is the reorientation of work within machine which involves time to disengage the work from die and again engage it after reorientation.The steps involved are :

(i) approach the clamp and grasp it

(ii) disengage the two clamps

(iii) unseat the work

(iv) index the work and bring it to a new position

(v) align and seat the work

(vi) reach the clamps and engage them

(vii) move away the arms.

Here again the time involved in each substep is determined using the standard time data[7] and an allowance of 40% is added to calculate the time for reorientation of work.

4.6 ALGORITHM FOR THE PROGRAM DEVELOPED

The plan for generation of operation sequences involves three basic steps as discussed below.

Ist Step

Identification of Blank Shape, Size and Reference Axes w.r.t. Blank and Input of Press Specification.

(a) Determination of Blank type

* Circular

* Polygonal

(b) Input of co-ordinates required, w.r.t. user's own reference.

(c) Giving the reference co-ordinates and reference axes, w.r.t. which subsequent co-ordinates should be given.

(d) Input of sheet Metal thickness.

(e) Input of stroke length and ram velocity.

IInd Step

Identification of Geometric Features, their Location and Dimensions

(a) Determination of class of feature according to the features char, C-4.2.1

(b) Input of required parameter for dimensioning and location of feature.

(c) Calculations for location and dimensioning.

(d) Calculations for generation of data regarding the minimum distance required between features and minimum tolerance achievable for the features in the mild steel sheet.

IIIrd Step

Generation of Feature Relationship Matrix

(a) Calculation of distance of a feature with other features to be generated.

(b) Comparison of the distance with the minimum distance data. If distance is less, then taking input of the tolerance to be achieved in feature.

(c) Comparison of the tolerance with minimum tolerance data.

(d) Regrouping of features within same class, if precedance is required on some element.

(e) Determination of value for corresponding elements of feature relationship matrix

fij = 0, if there is no relationship between features i & j

fij = 1, if feature 'i' cannot be made unless feature 'j' has been made
or when 'i' is equal to 'j'.

IVth Step

Generation of Feasible Operation Sequences.

(a) Input of number of features, obtained finally after regrouping.

(b) Generation of various permutations and comparison with the feature relationship matrix to determine the feasible sequences.

Vth Step

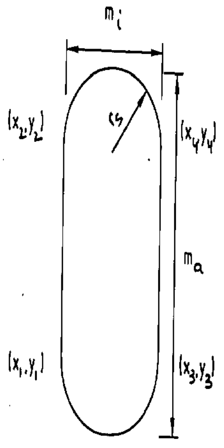
Evaluation of Feasible Operation Sequences

(a) Input of feasible operation sequences, operation types and dimension of features

(b) Determination of number of tool setup changes and machine changes.

(c) Calculation of manufacturing time for different sequences of operation using the above obtained data and standard time data.

(d) Sorting of operation sequences based on minimum manufacturing time for a component.



OVAL

Fig. 4.6 Type of

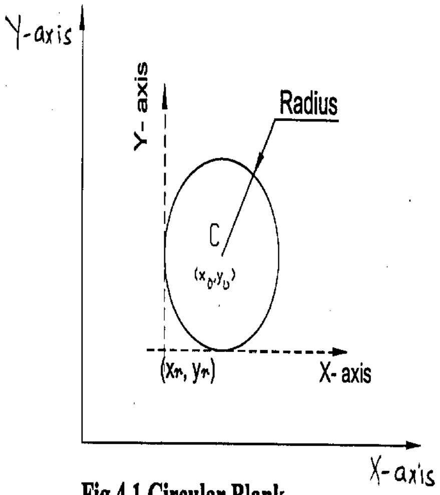


Fig 4.1 Circular Blank

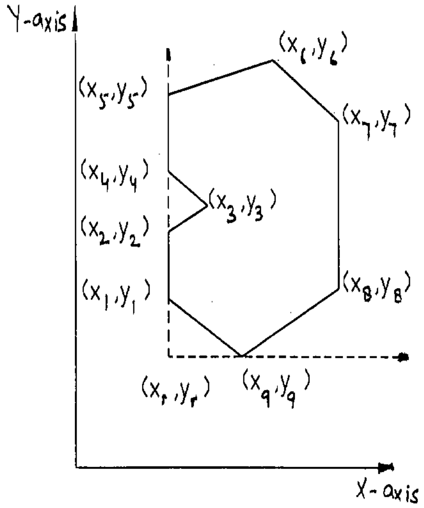


Fig 4.2 Polygonal Blank

Fig 4.3 Thickness of Sheet

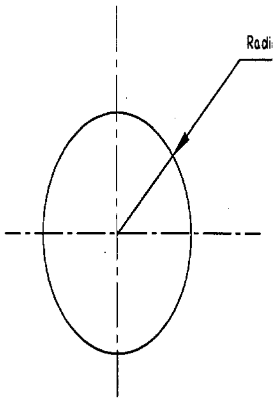


Fig. 4.4 Dimensioning a Ho

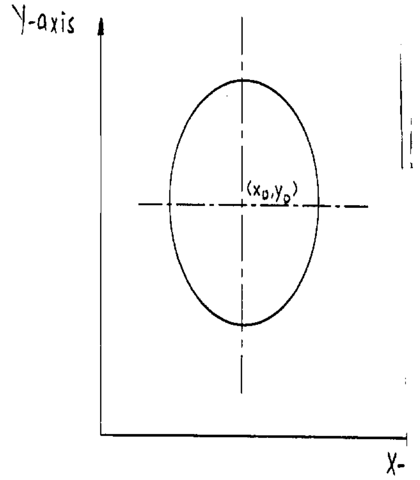


Fig. 4.5 Locating a Hole

5.1 INPUT OF DATA

Input of Blank Shape and Size

The blank shape is selected as polygonal and subsequently the number of edges are input as 4. Co-ordinates of the blank are given w.r.t. any user's defined reference. Here the co-ordinates are given as shown in Fig. 5.1. The program then determines the minimum of X-coordinate and Y-coordinate, and assigns this as a reference for subsequent input of feature dimensions. And the coordinatres for the edges are given as shown in the Fig. 5.2

Thickness of sheet metal (2mm) is also input to the program.

Input of Feature Dimensions and Locations

The dimensions and the locations of various features to be generated in the component are then given as input to the program. Their locations are given w.r.t. the new reference axis, given by the program.

Similar features having same dimensions can be combined into groups, and this number of groups is given as an input, so that the program will take input of the given number of group of features.

In the first component there are following 6 group of features

1. 4 holes of 2 mm radius.
2. 6 holes of 4 mm radius.
3. 1 slot of 5 mm minor dimension
4. 1 U-bend of 13 mm radius of fillet.
5. 2 flanges each of 12 mm radius with 45^0 angle.
6. 2 hems.

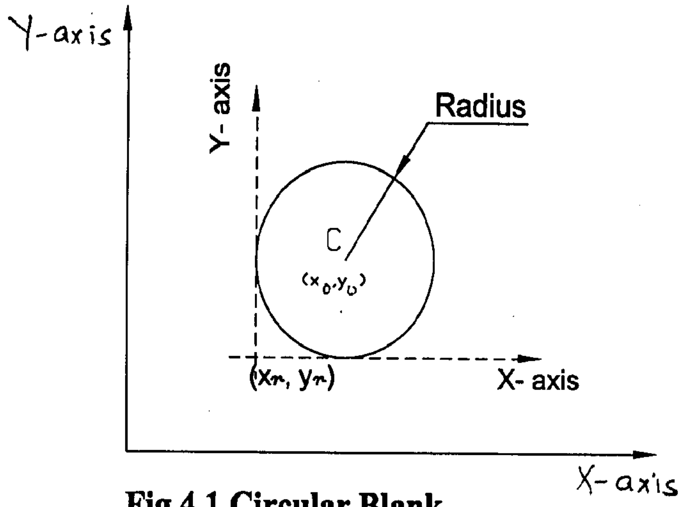


Fig 4.1 Circular Blank

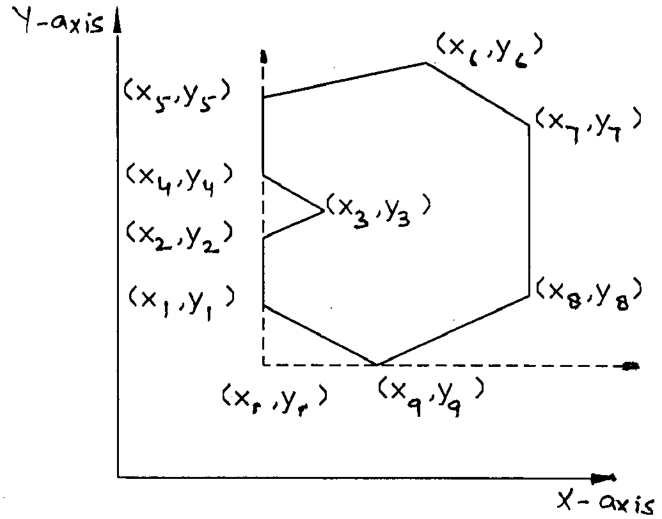


Fig 4.2 Polygonal Blank

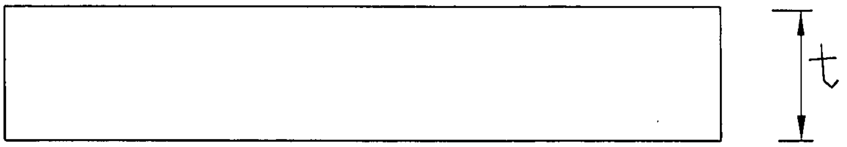


Fig 4.3 Thickness of Sheet

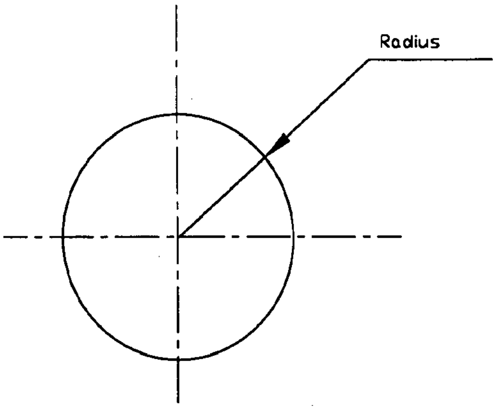


Fig. 4.4 Dimensioning a Hole

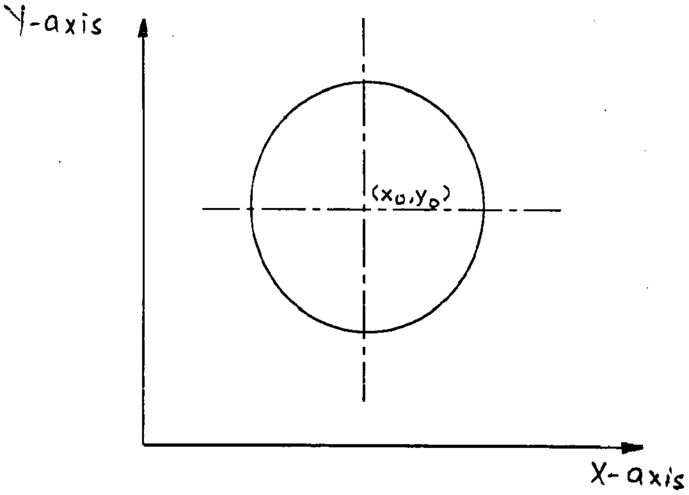


Fig. 4.5 Locating a Hole

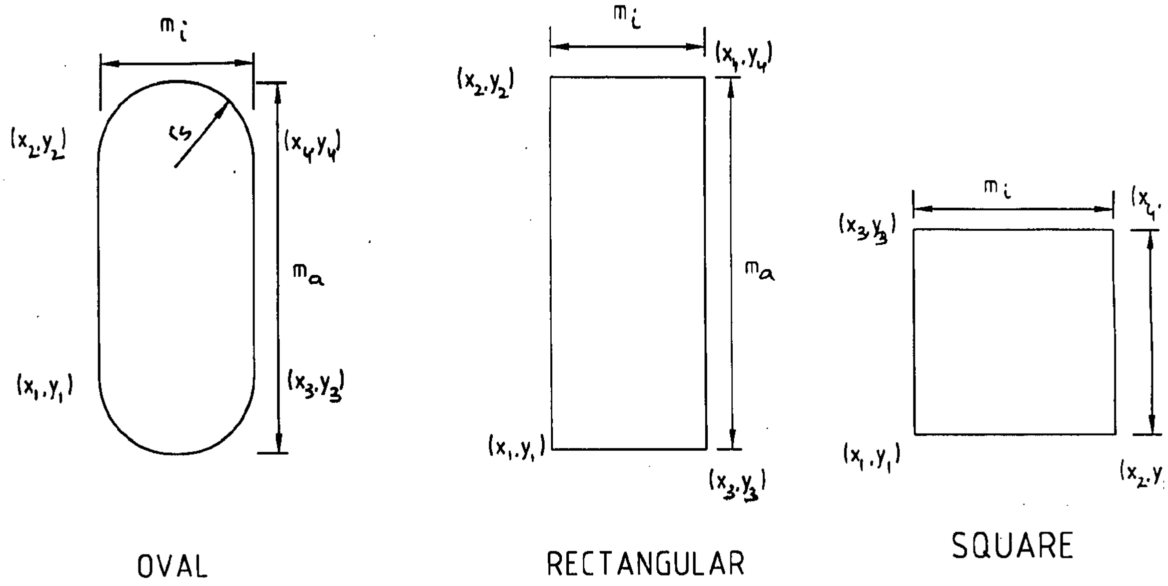
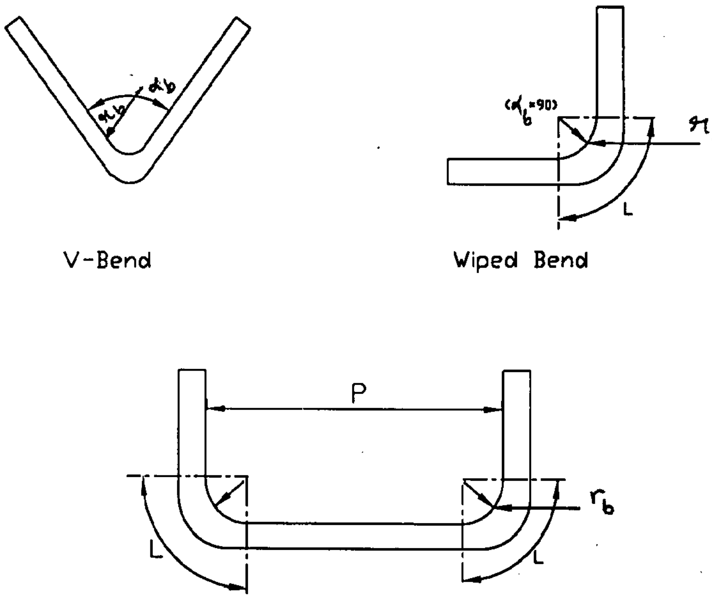


Fig. 4.6 Type of Slots

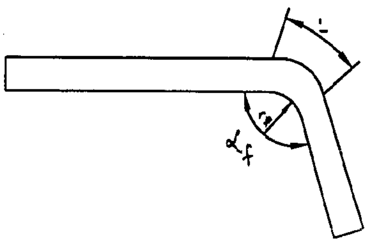


V-Bend

Wiped Bend

U-bend

Fig. 4.7 Type of Bends



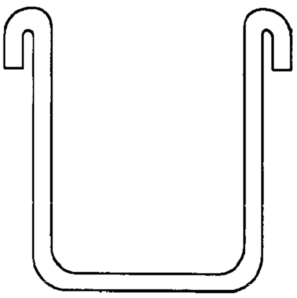


Fig. 4.8 Flange

Fig. 4.9 Hem

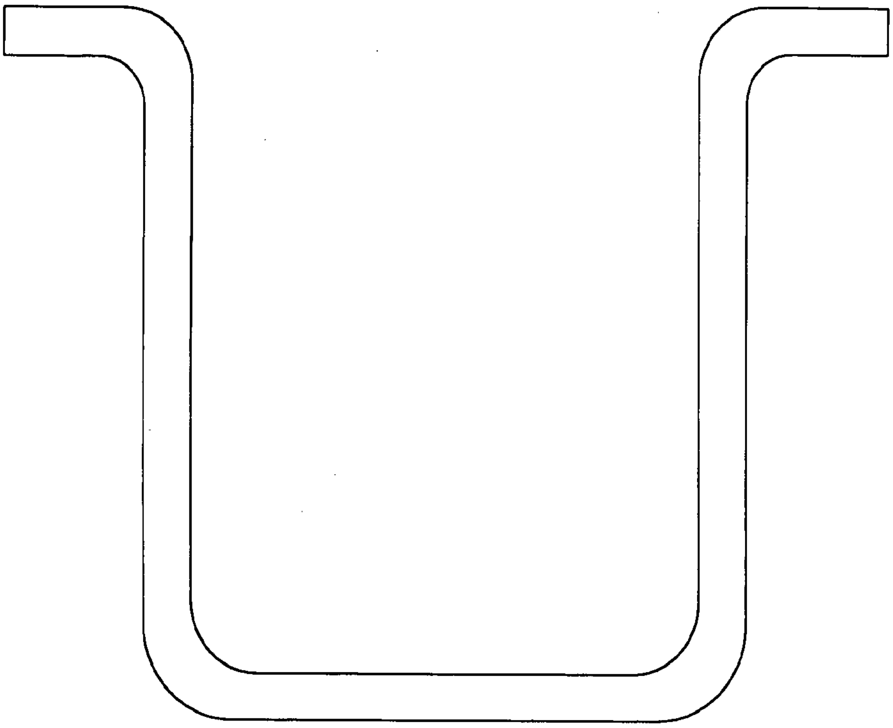
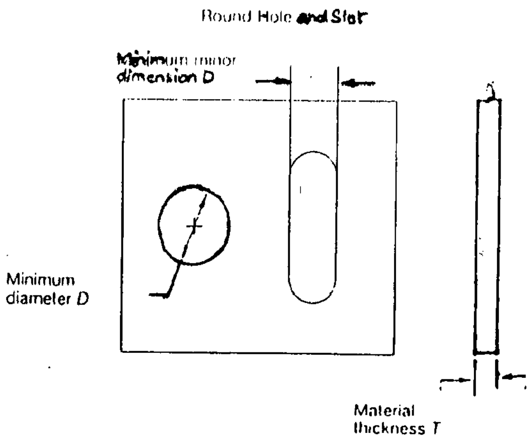
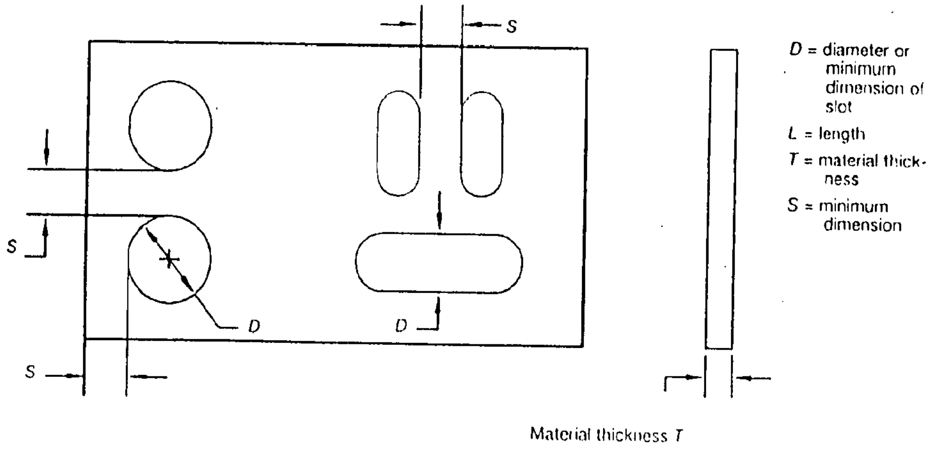


Fig. 4.10 A Draw



Rule: Minimum (D) = T or 0.4 in., whichever is larger

Figure 4.11
Minimum Dimension for Holes and Slots



Rules:

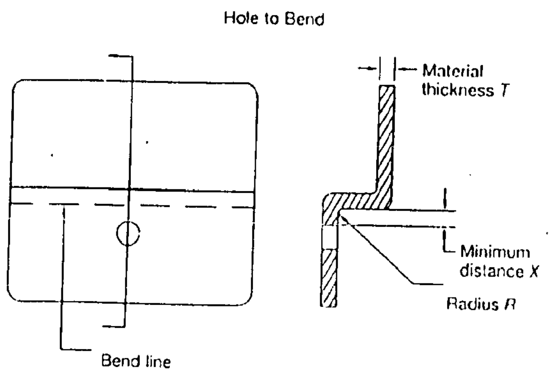
For $T < D < 5T$: Min $(S) = 1.5T$

For $5T < D < 10T$: Min $(S) = 2.0T$

For $D > 10T$: Min $(S) = 3.5T$

For $T < L < 10T$: Min $(S) = 2.0T$

Figure 4.12
Minimum Hole-to-Hole/Hole-to-Edge Distance



Rule: Minimum $(X) = 2T + R$

Figure 4.13
Minimum Distance Between a Hole and a Bend

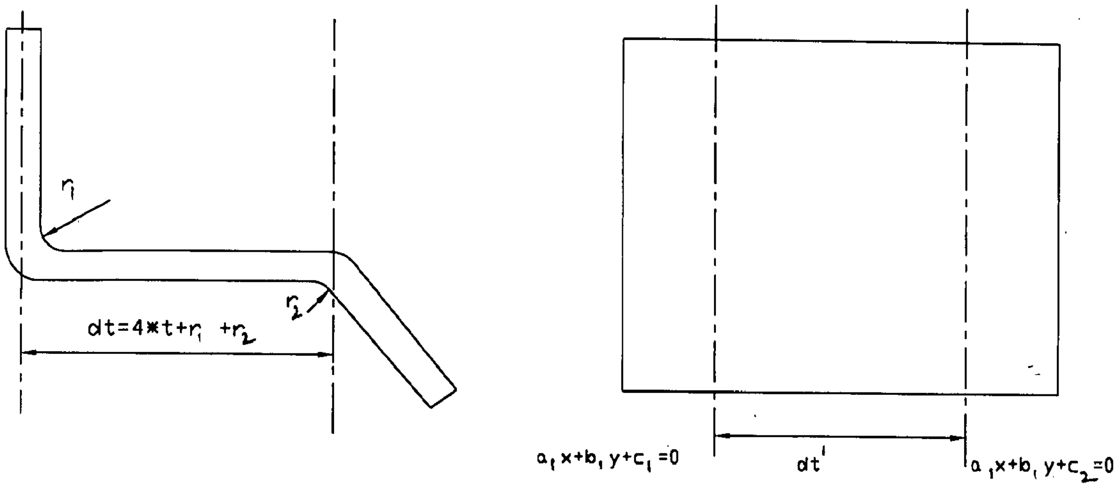


Fig. 4.14 Distance Between Formed Features

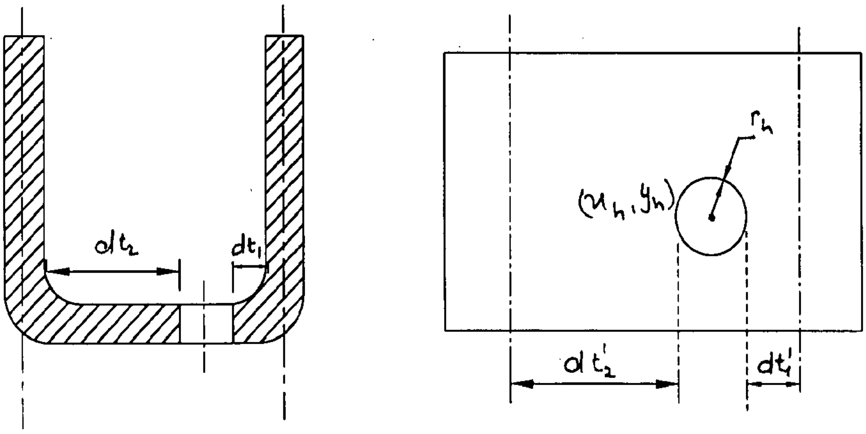


Fig. 4.15 Distance of Hole from a Formed Feature

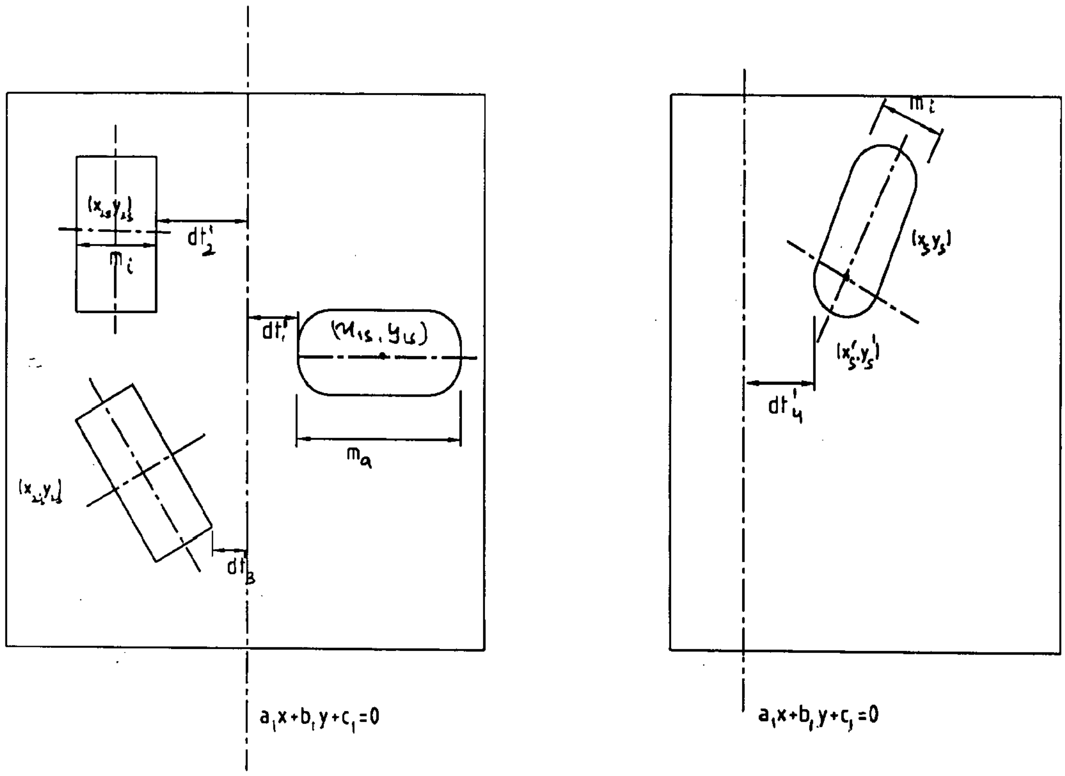


Fig. 4.16 Distance of Slots from Formed feature

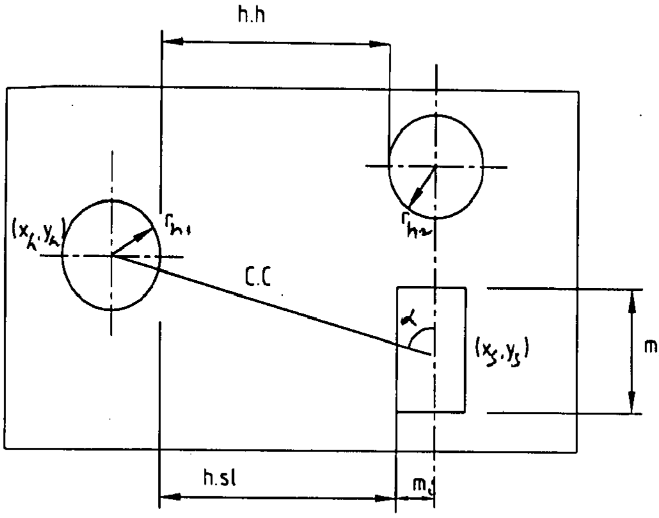


Fig. 4.17 Distance of a Hole from Other Hole/Slot

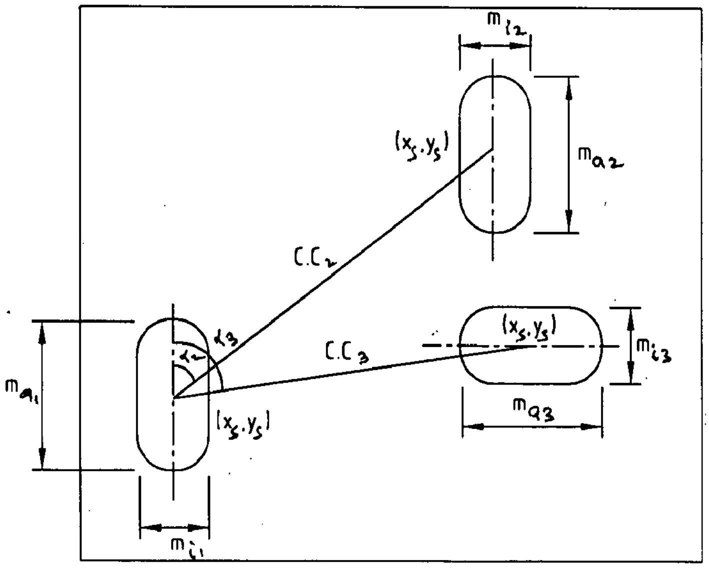


Fig. 4.18 Distance between Slots

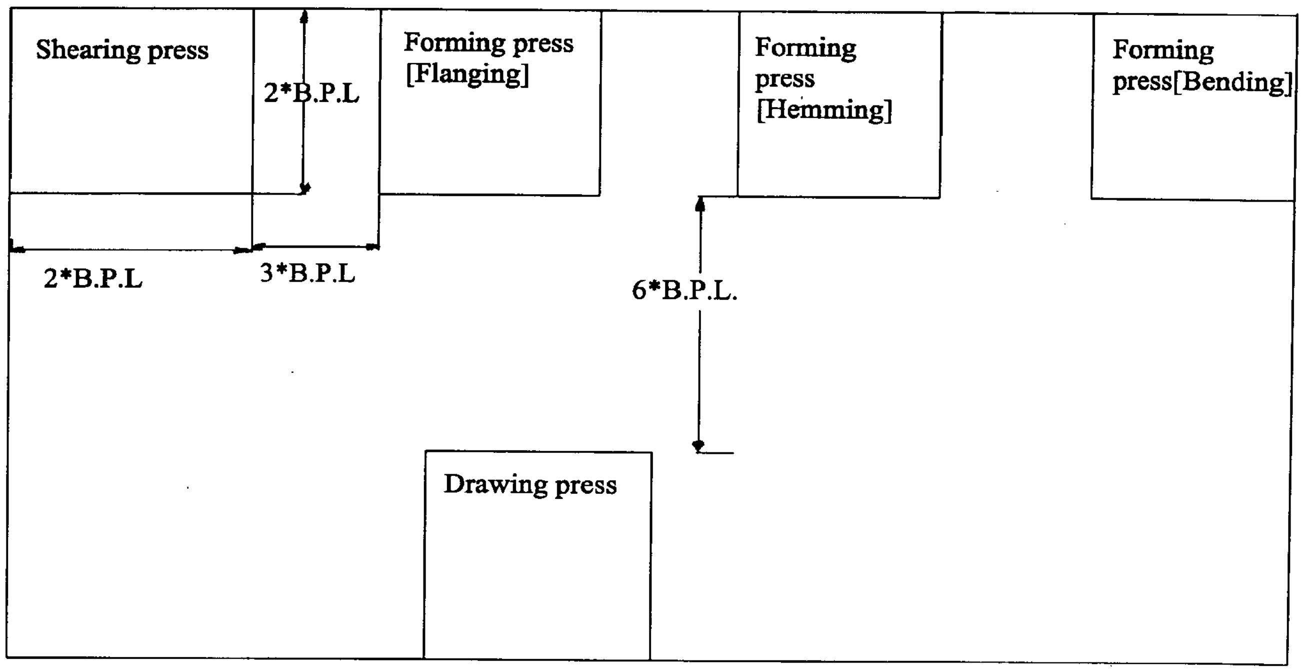
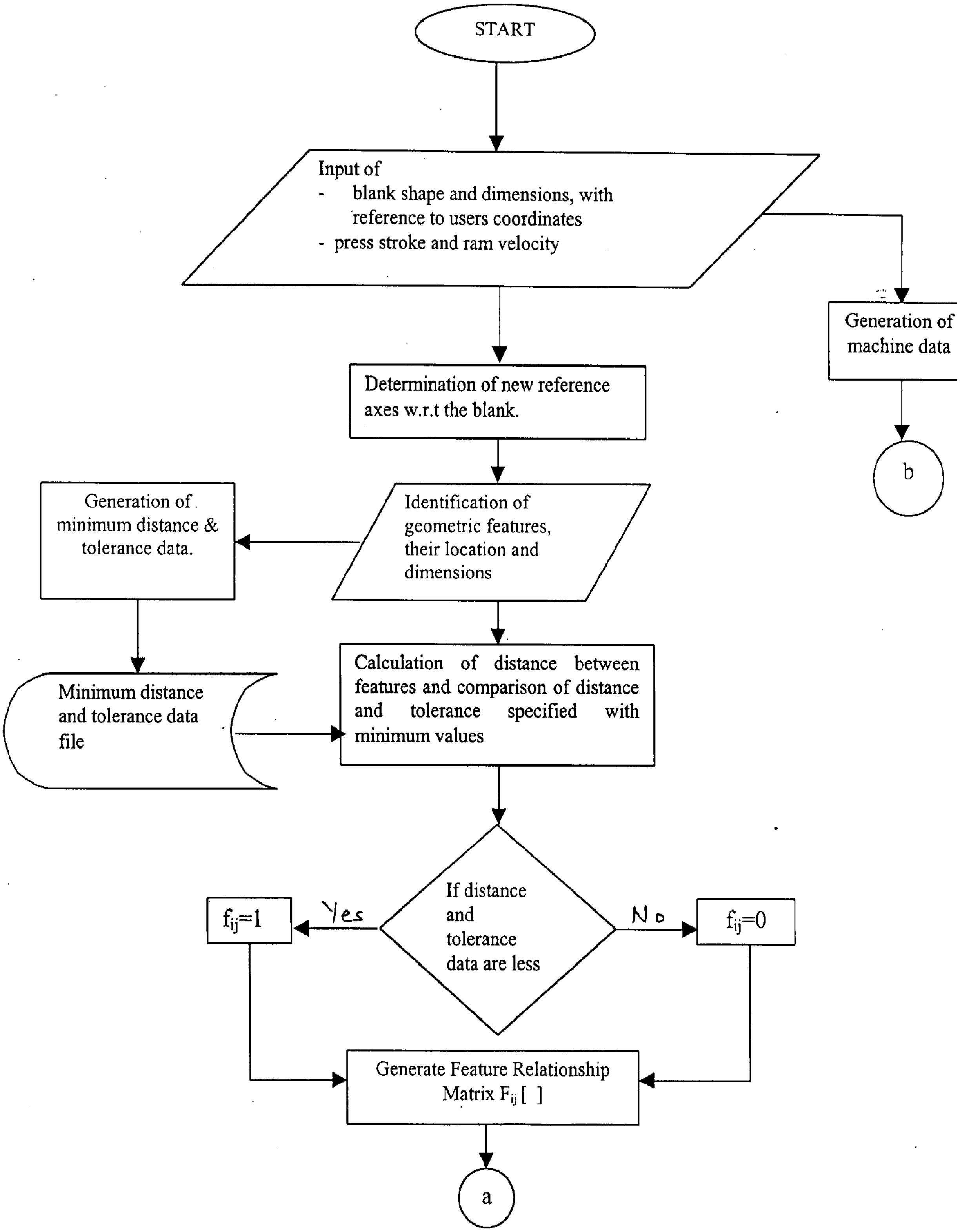


Fig. 4.19 Plan for Machine Layout

B.P.L= BOLSTER PLATE LENGT

B.P.W= BOLSTER PLATE WIDTH


START
Input of
- blank shape and dimensions, with reference to users coordinates
- press stroke and ram velocity
Generation of machine data
b
Determination of new reference axes w.r.t the blank.
Generation of minimum distance & tolerance data.
Identification of geometric features, their location and dimensions
Minimum distance and tolerance data file
Calculation of distance between features and comparison of distance and tolerance specified with minimum values
If distance and tolerance data are less
Yes
No
$f_{ij}=1$
$f_{ij}=0$
Generate Feature Relationship Matrix F_{ij} [ ]
a

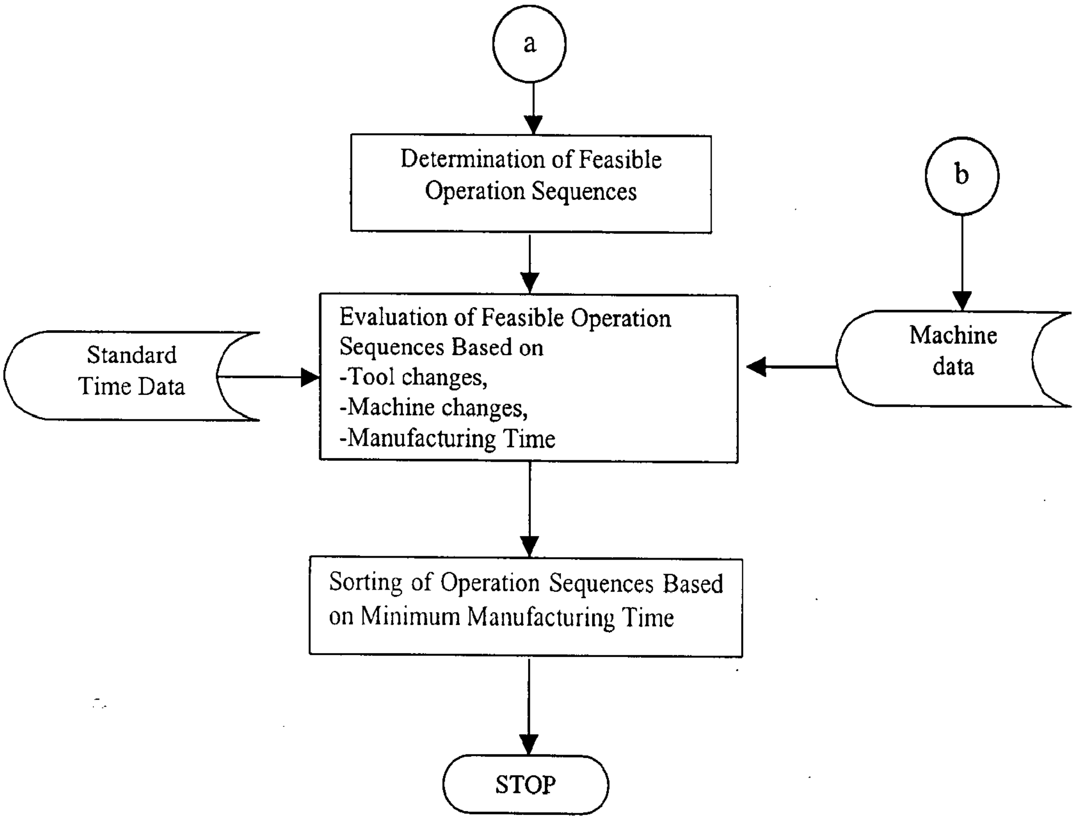


Fig. 4.20 Flow chart for the program developed

CHAPTER 5

RESULTS AND DISCUSSION

The computer program discussed in chapter 4 has been used to generate the feasible operation sequences for three components (designated as P_1, P_2 and P_3). These sequences are further evaluated on the basic of three basic criteria, number of tool changes, machine changes required and manufacturing time of the part Feasible sequences are finally ranked on the basis of the above coonsideratios. The discussed part examples involve various features considered in the software. The precedance matrix betweeen group of features is generated based on various rules, discussed in article 4.3.1, by calculating the distances between the different features. Using these precedances in feature relationship matrix, set of feasible operation sequences are generated. The number of tool changes and machine changes involved in each sequence are then determined. Then the time required for the production of a component with the above identified feasible sequences is calculated using the standard time data. Finally they are ranked on the basis of minimum manufacturing time. The results for these three components have been presented in Appendics [2].

DISCUSSION

To have an understanding of the steps involved, the procedure has been discussed for the first component. The steps involved have been discussed below.

5.1 INPUT OF DATA

Input of Blank Shape and Size

The blank shape is selected as polygonal and subsequently the number of edges are input as 4. Co-ordinates of the blank are given w.r.t. any user's defined reference. Here the co-ordinates are given as shown in Fig. 5.1. The program then determines the minimum of X-coordinate and Y-coordinate, and assigns this as a reference for subsequent input of feature dimensions. And the coordinatres for the edges are given as shown in the Fig. 5.2

Thickness of sheet metal (2mm) is also input to the program.

Input of Feature Dimensions and Locations

The dimensions and the locations of various features to be generated in the component are then given as input to the program. Their locations are given w.r.t. the new reference axis, given by the program.

Similar features having same dimensions can be combined into groups, and this number of groups is given as an input, so that the program will take input of the given number of group of features.

In the first component there are following 6 group of features

1. 4 holes of 2 mm radius.
2. 6 holes of 4 mm radius.
3. 1 slot of 5 mm minor dimension
4. 1 U-bend of 13 mm radius of fillet.
5. 2 flanges each of 12 mm radius with 45^0 angle.
6. 2 hems.

The number of similar features in each group is also given as input. While giving the input of feature locations and dimensions, the classification pattern depicted in the chart C-4.2.1 is followed.

For the first group of features, the co-ordinates of 4 whole centers are given after giving the radius of those holes. Similarly, the dimension and locations of 6 holes of second group of features are input.

For the third group, i.e., oval slot of minor dimension 5 mm, this minor dimension is given as input. The orientation of slot w.r.t the horizontal axis is specified as vertical and the location is specified by giving co-ordinates of straight edgte, i.e., (130,47) and (130,53). The program calculates the major dimension using equation 4.2.1 as 11 mm.

For the fourth group of feature, i.e., U-bend, its radius of fillet, 13 mm is given as input. The co-ordinates of ends of bend line are given as input after giving the orientation to be vertical. The program takes as input distance between the parallel U-bend lines, 75 mm. Using the radius of fillet, then the bend length is calculated to be 21.677 mm using equation 4.2.4. Equation of the bend lines is also calculated using equaiotn 4.2.5 as

$X-95 = 0$

and $X-170 = 0$

For the fifth group of features, i.e., two flanges, the radius of curvature (12 mm) and angle of flange surfaces (45^0) are given followed by the co-ordinates of the flange lines (45,0); (45,100) and (220,0); (220,100). The program calculates the form length using radius and angle of flange as input in the equation 4.2.4, as 10.05 mm. Equation of flange lines is also calculated using equation 4.2.7 as

$$X-45 = 0$$

$$X - 220 = 0$$

Finally, for the sixth group of features, the two hems, the co-ordinates of hem-line should be given as input. Program gives the equation of hem lines using equation 4.2.8 as

$$X-5 = 0$$

$$X-260=0$$

5.2 DETERMINATION OF PRECEDANCE BETWEEN FEATURES

In order ot properly acheive the required specification on the features, some precedance are set among them. This also helps to determine the sequence in which operations should be carried so as to obtain the final part.

PRECEDANCE AMONG FORMING FEATURES

Since, the forming operations involved are of three different types, the distances among them need not be calculated. But based on the guidelines, summarised in the section 4.3.1 following sequence should be followed for three forming operations.

Flange - hem - bend

Thus, for the feature relationship matrix, values for three elements are known

f_{45} = 1 (Bend should be made after flange)

f_{46} = 1 (Bend should be made after hem)

f_{65} = 1 (Hem should be made after flange)

PRECEDANCE BETWEEEN SHEARING AND FORMING FEATURE

To determine precedance between shearing and forming features, the distance between them needs to be determined. Distance of each of the shearing feature from forming features is determined one by one. If any of the distance is less than the minimum required (discussed in the article 4.3.3) and the tolerance specified is also less, than the corresponding shearing feature should be made after that formed feature has been made.

Distance of a hole from a formed feature can be calculated using equations 4.3.7 and 4.3.8. For example, distance of the hole located at (110,10), having radius 2mm from U-bend is calculated as follows :

the equations of U-bend lines are:

$$X-95 = 0$$

$$X-170 = 0$$

and the bend length, as calculated is 21.677 mm. In equation 4.3.7

$$dt_1' = \left\| \frac{1x110+0-95}{1} \right\| - 2 = 13$$

$$dt_2' = \left\| \frac{1x110+0-170}{1} \right\| - 2 = 58$$

Then using equation 4.3.8

$$dt_2 = 13 - 21.677/2 = 2.16 \text{ mm}$$

$$dt_2 = 58 - 21.677/2 = 47.16 \text{ mm}$$

Since, U-bend involves bend along two lines with same dimensions, minimum of the above two distances is taken as the distance of the hole from U-bend.

Thus, the distance of hole-1 of feature group 1 from U-bend 1 (feature group 4) is

$dt_1 = 2.16$ mm

But this is less than the minimum distance required between hole and bend, to avoid distortion of existing hole while bending is done. (Calculated using equation 4.3.5 as 17 mm). Besides, the tolerance on hole location w.r.t. bend is also less (0.13 mm). So this hole should be made after U-bending has been done.

Similarly, distance of other holes from the formed features can be calculated and precedance relationship can be determined. For the hole group 1 these have been tabulated as below.

Sl.No.	Hole location	Distance (mm) and precedance					
		U-bend		Flange		Hem	
		Dist.	Pre.	Dist.	Pre.	Dist.	Pre.
1	(110,10)	2.16	after	59.97	none	105	none
2	(110,90)	2.16	after	59.97	none	105	none
3	(155,10)	2.16	after	59.97	none	105	none
4	(155,90)	2.16	after	59.97	none	105	none

Table 5.2.1 Distance of group 1 holes from formed features

Thus, we can say that this group of holes should be made after U-bend. Hence, values for the following elements of feature realtionship matrix can be assigned.

$f_{14} = 1$, (hole group-1 should be made after U-bend)

$f_{15} = 0$, (no relation with flange feature)

$f_{16} = 0$, (no relation with hem features)

The distances and precedance relationship for hole group-2 (feature group-2), with the formed features are tabulated below

Sl.No.	Hole location	Distance (mm) and precedance					
		U-bend		Flange		Hem	
		Dist.	Pre.	Dist.	Pre.	Dist.	Pre.
1	(15,50)	69.16	none	24.97	none	10	after
2	(60,15)	24.16	none	9.97	after	55	none
3	(60,85)	24.16	none	9.97	after	55	none
4	(205,15)	24.16	none	9.97	after	55	none
5	(205,85)	24.16	none	9.97	after	55	none
6	(250,50)	69.16	none	24.97	none	10	after

Table 5.2.2 Distance of hole group-2 from formed features

Using above table, we can regroup these holes, with holes in the same group having similar relationships with the formed features. If we make a new group of features including hole number 1 and 6 and removing them from the second group of features, we can have similarity of feature relationships. This group of features can be assigned number 7, in addition group to the previously considered 6 group of features. And we can assign following values to the elements of feature relationship matrix.

For group-2 features

$f_{24} = 0$, (no relation of with bend feature)

$f_{25} = 1$, (group-2 features should be made after flange features-5)

$f_{26} = 0$, (no relation with hem features)

For group-7 features

$f_{74} = 0$, (no relation with bend feature)

$f_{75} = 0$, (no relation with flange features)

$f_{76} = 1$, (group-7 featurs should be made after hem features-6).

Distance of the slot (feature group-3) from formed features can be calculated using equation 4.3.9 and 4.3.10. For example, its distance from U-bend can be calculated as follows :

Using equation 4.3.9, (the slot being parallel to the bend line).

$$dt_1' = \left\| \frac{1x132.5-95}{1} \right\| - \frac{5}{2} = 35 \text{ mm}$$

$$dt_2' = \left\| \frac{1x132.5-170}{1} \right\| - \frac{5}{2} = 35 \text{ mm}$$

and in the equation 4.3.10

$$dt_1 = 35 - 21.677/2 = 24.16 \text{ mm}$$

$$dt_2 = 35 - 21.677/2 = 24.16 \text{ mm}$$

Thus, its distance from the U-bend is 24.16 mm which is more than the minimum distance required (calculated using equation 4.3.5 as 17 mm) to avoid distortion of pre-existing slot while U-bend is made.

Similarly, the distance of this slot from other formed features are :

from, flange : dt = 79.97 mm

from hem : dt = 125 .mm

These distances are more than the minimum required. Hence, the slot, if made before forming operations is unlikely to be distorted during forming operations. Here, using this guidelines summarised in section 4.3.1 we can assign following values to the elements in feature relationship matrix.

f_{43} = 1 (U-bend feature [4] should be made after shot [3])

f_{53} = 1 (flange features [5] should be made after slot [3])

f_{63} = 1 (hem features [6] should be made after slot [3])

PRECEDANCE AMONG SHEARING FEATURES

If the distance between shearing features is less then the minimum safe distance, which is function of the sheet thickness (Fig [4.12]), and tolerance on their location is also less, then precedance should be maintained among operations for these features.

The distance of a shearing feature from other group of shearing features is calculated by the procedure, prescribed in article 4.3.3. These distances have been tabulated below.

For feature group-1

Sl.No.	Hole location	Distance (mm) and precedance					
		Feature Gr.2		Feature Gr.3		Feature Gr.7	
		Dist.	Pre.	Dist.	Pre.	Dist.	Pre.
1	(110,10)	44.25	none	32.5	none	97.08	none
2	(110,90)	44.25	none	32.5	none	97.08	none
3	(155,10)	44.25	none	32.5	none	97.08	none
4	(155,90)	44.25	none	32.5	none	97.08	none

Table 5.2.3 Distance of Hole Group-1 from other Sheared Feature Groups.

For feature group-2

Sl.No.	Hole location	Distance (mm) and Precedance			
		Feature Gr.3		Feature Gr.7	
		Dist.	Pre.	Dist.	Pre
1	(60,85)	25.5	none	49.00	none
2	(60,15)	25.5	none	49.00	none
3	(205,85)	25.5	none	49.00	none
4	(205,15)	25.5	none	49.00	none.

Table 5.2.4 Distance of Hole Group-2 from other Sheared Feature Groups.

For feature group-3.

Its distance from group-7 feature is 111 mm and this is safe enough. Hence, no precedance relation exists among them.

Thus, based on above calculation of distances, values for following elements of feature relationship matrix are assigned 'O'

$* f_{12} = f_{21} = 0$

$* f_{13} = f_{31} = 0$

$* f_{17} = f_{71} = 0$

$* f_{23} = f_{32} = 0$

$* f_{27} = f_{72} = 0$

$* f_{37} = f_{73} = 0$

Based on the above calculations, the feature relationship matrix, shown in App.2 [P1.3] is generated.

5.3 GENERATION OF FEASIBLE OPERATION SEQUENCES

The feasible operation sequences out of 7 ! possible arrangements are then determined using the above feature relationship matrix Fij [ ]. Each of the 7! arrangements are verified using this feature relationship matrix. The infeasible ones are rejected while feasible ones are selectred for further evaluation.

All the feasible operation sequences for part P_1 have been shown in the App.2 [P1.4].

5.4 EVALUATION OF FEASIBLE OPERATION SEQUENCES

The obtained feasible operation sequences are then avaluated based on three criteria :

(a) tool changes

(b) machine changes

(c) manufacturing time for a part

5.4.1 TOOL CHANGES

In this work, the tool changes are assumed to be required in two cases, mentioned in article 4.5.1. Based on these cases, the number of tool changes required in each operation sequences are determined and have been shown in the App.2 [P1.3].

In the fourth sequence, the tool setup on the shearing machine needs to be changed 3 times when :

(a) feature group-2 (radius 4mm) is to be made after slotting (group-3) on the flanged component.

(b) feature group-7 (radius 4 mm) is to be made on the component after flanges, hems and bend has been made.

(c) feature group-1 (radius 2mm) is to be made subsequent to the group-7 features.

While in the first sequence, only two tool set up are required when :

(a) feature group-2 and 7 (each of same radius-2mm) are to be made after slotting on the component which has been flanged and hemmed already.

(b) feature group-1 (radius 2mm) is made on the component afer bending operation has been done.

Thus, the operation sequences are evaluated for number of tool setup changes required.

5.4.2 MACHINE CHANGES

Number of machine changes required for each operation sequences are determined, based on the cases as mentioned in article 4.5.2.

This is seen that maximum number of machine changes are required for fourth sequence, which suggests a change of operatrion type after each step. While for the sequences 2,3,11,12 machine changes are required only 4 times as they suggest to perform more than one operations of same type whenever possible, before changing the machine.

5.4.3 MANUFACTURING TIME OF THE PART

NON-PRODUCTIVE TIME ELEMENTS

For this, the press tonnage for both shearing and forming operations is determined.

For shearing operation :

F_s = S x parimeter of slot x thickness

where,

S = shearing strength of the (0.5% carbon) steel

= 35 tons per square inch

= 531.6 N/mm^2

perimeter of slot = $2x6 + 2\pi x5$

= 43.42 mm.

Hence, F_s, the shearing load

= 531.6 x 43.42 x 2 = 46.164 KN

= 4.71 tons.

So shear press tonnage required =

F.O.S. x F_s = 5 x 4.71 = 23.55 tons

For forming operations :

This is calculated using the pad force required. The values when put in equation (2.2.3)

$\therefore F_p = 0.67 \times 531.6 \times 100 \times 2 = 71.23$ KN

$= 7.27$ tons

So, form press tonnage required is

$F.O.S. \times F_p = 5 \times 7.27 = 36.3$ tons.

Using the press tonnage, the dimensions of bolster plate and die are taken from data table [1] (which are placed as data files in the program)

For shearing press :

- length of bolster plate = 20 inches.
- width of bolster plate = 12 inches
- distance between die clamps = 11 inches.

For forming press :

- length of bolster plate = 28 inches.
- width of bolster plate = 18 inches.
- distance between die clamps = 17 inches

Using the above determined data, the data for various non-productive time elements are determined (using steps meationed in section 4.5.3.1)

- Time for tool setup change (die) on the shearing press

  = 10715 x 1.4 = 15001 tmu

  = 90 sec.

- Time for machine changes

  The distances among machines are determine for the layout, plan shown in Fig. 4.19. Hence, the time for machine change overs among:

- * shearing press and forming press for flanging = 13.62 sec.
- * shearing press and forming press for hemming = 16.02 sec
- * shearing press and forming press for bending = 18.42 sec.
- * forming press for flanging and forming press for hemming = 14.22 sec.
- * forming press for flanging and that for bending = 16.62 sec
- * forming press for hemming and that for bending = 14.22 sec.

- Work reorientation time within a press = 11 sec.

PRESS WORKING TIME ELEMENTS

With the stroke length given as 1.5 m and velocity of ram as 0.3 m/sec, the time for ram travel comes out to be 5 sec. On which the 40% time is added for rams movement into the die and its dwell, thus giving total operation time as 7 sec.

Using these data for various time elements, the manufacturing time for the feasible operation sequences is determined. As an illustration, this has been calculated for the fifth operation sequence.

Operation 3 :

Work Orientation time = 11 sec
Press working time (slotting) = 7 sec

Operation 5 :

Machine change time = 13.62 sec.
Pressworking time (flanging) = 7 sec.

Work reorientation time = 11 sec.

Press working time (flanging) = 7 sec.

Operation 2 :

Tool changeover time = 90 sec.

Time for 4 hole punching = 4x7 = 28 sec.

Time for 3 times work reorientation = 3 x 11 = 33 sec.

Operation 6 :

Machine changing time = 16.02 sec.

Time for 2 hemming operations = 2 x 7 = 14 sec.

Work reorientation = 11 sec.

Operation 4 :

Machine changing time = 14.22 sec.

Time for U-bending = 7 sec.

Operation 7 :

Tool change time = 9 sec.

Time for 2 hole punching = 2 x 7 = 14 sec.

Work reorientation time = 11 sec.

Operation 1 :

Tool change time = 90 sec.

Time for 4 hole punching = 4 x 7 =28 sec.

Time for 3 time work reorientation = 3 x 11 =33 sec.

And to the sum of all these times, the time for work removal and placing in the bin is added as 10 sec. Sum of all these times comes out to be 551.86 sec.

Similarly, the manufacturing time incurred for other operation sequences are calculated, These have been shown in the App.2 [P1.3].

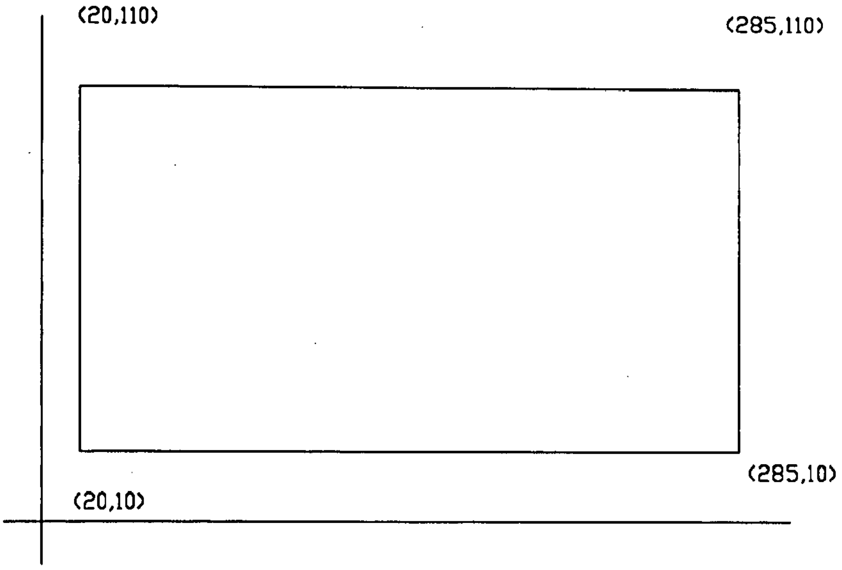


Fig. 5.1 Co-ordinates of Blank Given by User

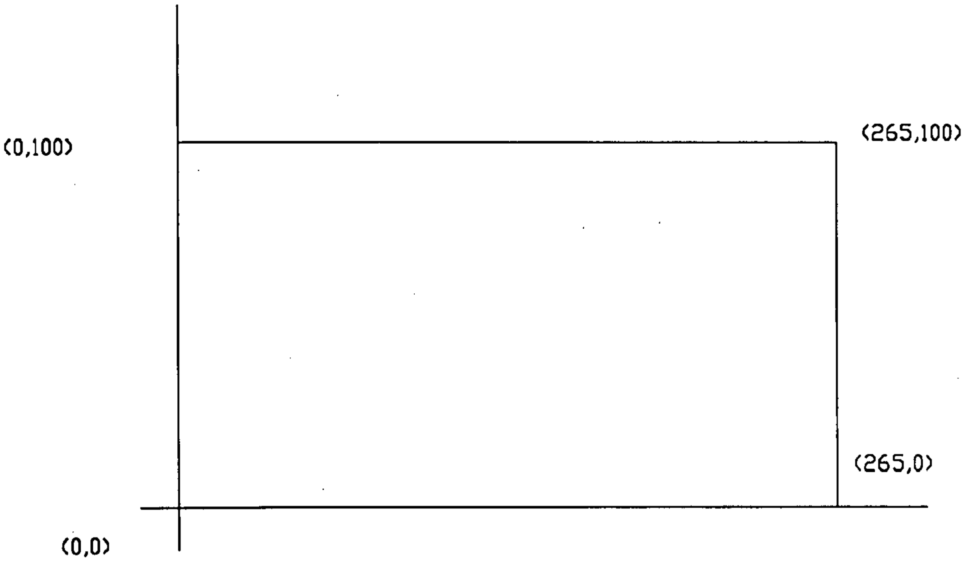


Fig. 5.2 Co-ordinates of Blank Modified by the Program

CHAPTER -6

CONCLUSIONS AND SCOPE OF FUTURE WORK

A scheme for generation and evaluation of operation sequences for the pressworking operations on a sheet metal part has been developed in the present work. The software is capable of considering circular and polygonal blanks. Besides, the operations for various features, depicted in the chart C-4.2.1 can be considered for the generation and evaluation of operation sequences. The software is flexible and can be adopted for other blank shapes and more operation types and features. The output of the software provides the feasible sequences of operations for given sheet metal component, and the evaluation of those operation sequences based on number of tool changes and machine changes required and the manufacturing time for that part.

In the present work, the input for the blank shape and size and the various geometrical features to be generated is given by the user. This work can be simplified, if the software is interfaced with a previously made drawing of the component on software packages such as Auto CAD. This will help in the automation of process planning because of interfacing with the design stage.

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APPENDIX-1

Table [illegible]1. Work-Factor Motion Time Table for Detailed Analysis
(Time in Work-Factor* Units)

Distance Moved, in.	Basic	Work-Factors				Distance Moved, in.	Basic	Work-Factors			
		1	2	3	4			1	2	3	4
(A) ARM—MEASURED AT KNUCKLES						(L) LEG—MEASURED AT ANKLE					
1	18	26	34	40	46	1	21	30	39	46	53
2	20	29	37	44	50	2	23	33	42	51	58
3	22	32	41	50	57	3	26	37	48	57	65
4	26	38	48	58	66	4	30	43	55	66	76
5	29	43	55	65	75	5	34	49	63	75	86
6	32	47	60	72	83	6	37	54	69	83	95
7	35	51	65	78	90	7	40	59	75	90	103
8	38	54	70	84	96	8	43	63	80	96	110
9	40	58	74	89	102	9	46	66	85	102	117
10	42	61	78	93	107	10	48	70	89	107	123
11	44	63	81	98	112	11	50	72	94	112	129
12	46	65	85	102	117	12	52	75	97	117	134
13	47	67	88	105	121	13	54	77	101	121	139
14	49	69	90	109	125	14	56	80	103	125	144
15	51	71	92	113	129	15	58	82	106	130	149
16	52	73	94	115	133	16	60	84	108	133	153
17	54	75	96	118	137	17	62	86	111	135	158
18	55	76	98	120	140	18	63	88	113	137	161
19	56	78	100	122	142	19	65	90	115	140	164
20	58	80	102	124	144	20	67	92	117	142	166
22	61	83	106	128	148	22	70	96	121	147	171
24	63	86	109	131	152	24	73	99	126	151	175
26	66	90	113	135	156	26	75	103	130	155	179
28	68	93	116	139	159	28	78	107	134	159	183
30	70	96	119	142	163	30	81	110	137	163	187
35	76	103	128	151	171	35	87	118	147	173	197
40	81	109	135	159	179	40	93	126	155	182	206
Weight, in lb:						Weight, in lb:					
Male..........	2	7	13	20	Up	Male..........	8	42	Up	—	—
Female........	1	3½	6½	10	Up	Female	4	21	Up	—	—

(T) TRUNK—MEASURED AT SHOULDER

1	26	38	49	58	67
2	29	42	53	64	73
3	32	47	60	72	82
4	38	55	70	84	96
5	43	62	79	95	109
6	47	68	87	105	120
7	51	74	95	114	130
8	54	79	101	121	139
9	58	84	107	128	147
10	61	88	113	135	155
11	63	91	118	141	162
12	66	94	123	147	169
13	68	97	127	153	175
14	71	100	130	158	182
15	73	103	133	163	188
16	75	105	136	167	193
17	78	108	139	170	199
18	80	111	142	173	203
19	82	113	145	176	206
20	84	116	148	179	209
Weight, in lb:					
Male	11	58	Up	—	—
Female	5½	29	Up	—	—

(F, H) FINGER-HAND—MEASURED AT FINGER TIP

1	16	23	29	35	40
2	17	25	32	38	44
3	19	28	36	43	49
4	23	33	42	50	58
Weight, in lb:					
Male	⅔	2½	4	Up	—
Female	⅓	1¼	2	Up	—

(Ft) FOOT—MEASURED AT TOE

1	20	29	37	44	51
2	22	32	40	48	55
3	24	35	45	55	63
4	29	41	53	64	73
Weight, in lb:					
Male	5	22	Up	—	—
Female	2½	11	Up	—	—

(FS) FOREARM SWIVEL—MEASURED AT KNUCKLES

45°	17	22	28	32	37
90°	23	30	37	43	49
135°	28	36	44	52	58
180°	31	40	49	57	65
Torque, lb-in.:					
Male	3	13	Up	—	—
Female	1½	6½	Up	—	—

Work-Factor* Symbols

W—Weight or Resistance
S —Directional Control (Steer)
P —Care (Precaution)
U —Change Direction
D —Definite Stop

The Work-Factor Company, Inc.

WALK TIME

Type	30-inch Paces 1	2	Over 2
General	Analyze from table	260	120 + 80 per Pace
Restricted		300	120 + 100 per Pace

Add 100 for 120–180° Turn at Start or Finish

Up Steps (8-inch rise—10-inch flat)	126
Down Steps	100

—

Head Turn:

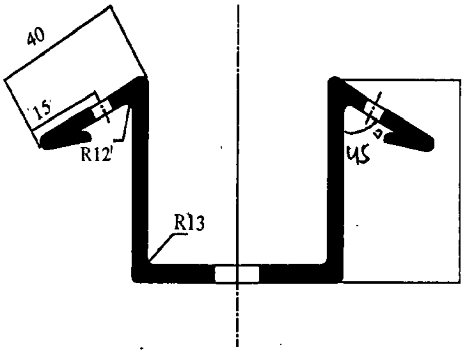
45°	40
90°	60

1 Time Unit = 0.006 second
= 0.0001 minute
= 0.00000167 hour

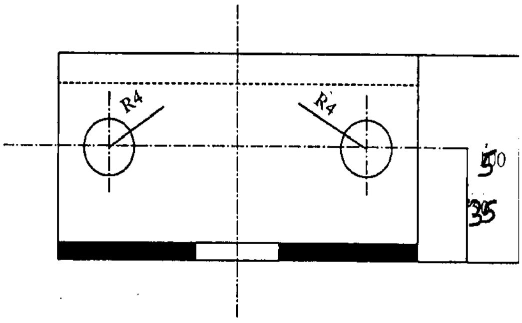
---

* Registered trademark.

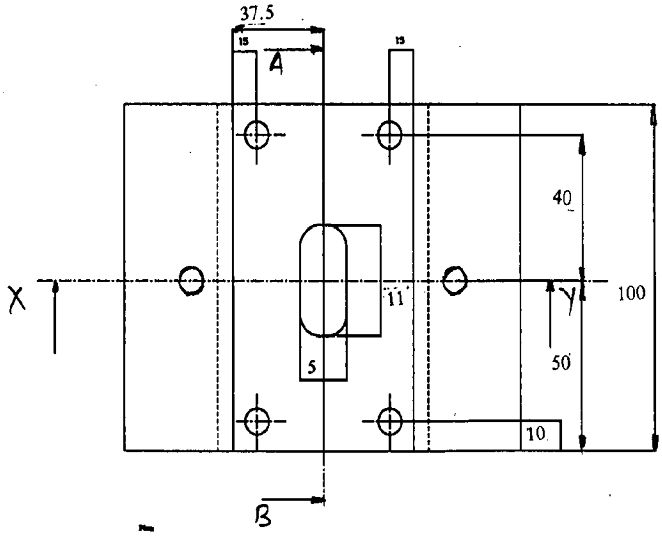
APPENDIX-2



Sectional Elevation on X-Y

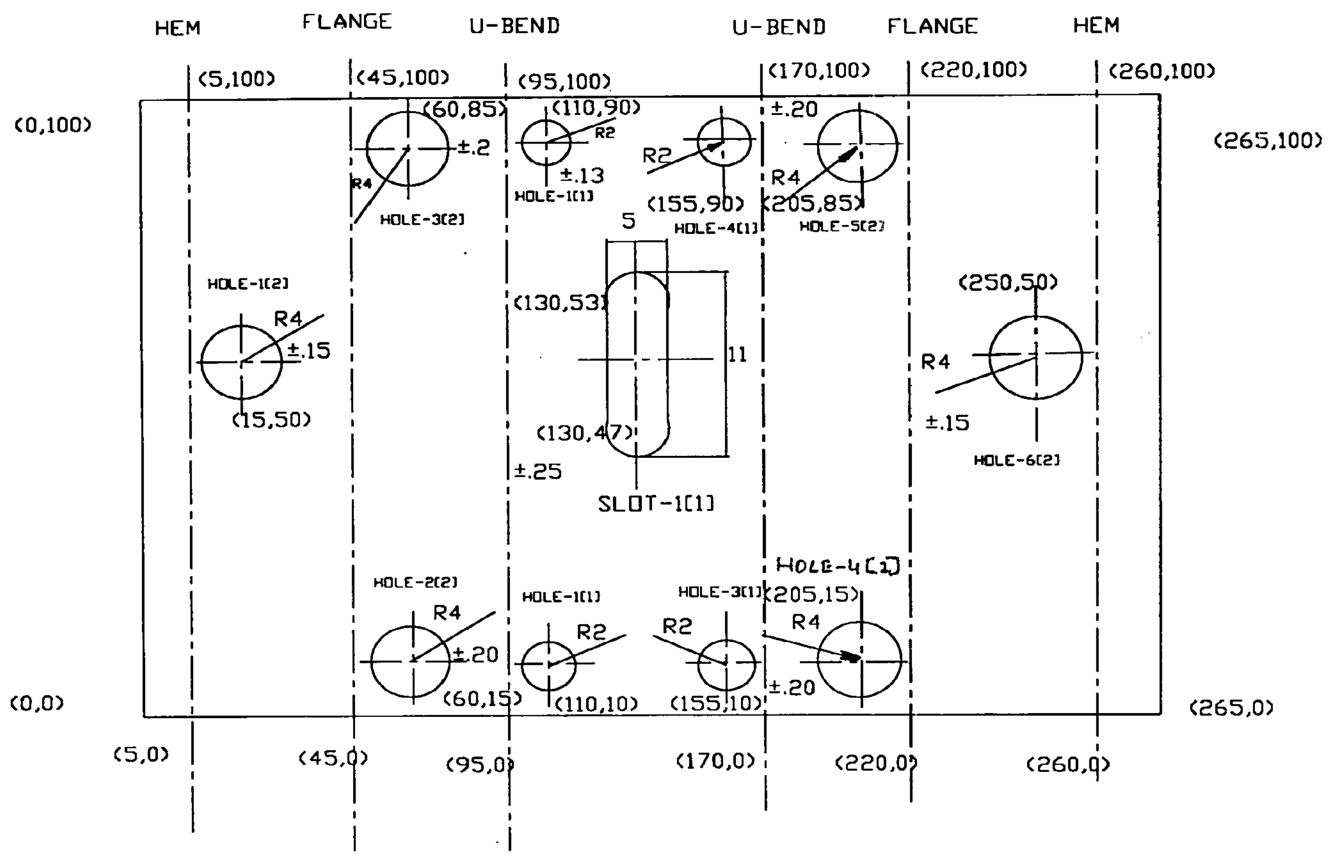


Section Side View on A-B



PLAN

App. P 1.1 Part-1



App. P-1.2 Operations on Blank

```
FEATURE RELATIONSHIPS DEVELOPED FOR THE GIVEN FEATURES ARE:-

                             1    2    3    4    5    6    7

[1] HOLE[2.00]               1    0    0    1    0    0    0
```

```
[2] HOLE[4.00]               0    1    0    0    1    0    0

[3] SLOT[5.00]               0    0    1    0    0    0    0

[4] BEND[13.00]              0    0    1    1    1    1    0

[5] FLANGE[12.00]            0    0    1    0    1    0    0

[6] HEM[0]                   0    0    1    0    1    1    0

[7] HOLE[4.00]               0    0    0    0    0    1    1
```

```
     1    0    0    1    0    0    0
     0    1    0    0    1    0    0
     0    0    1    0    0    0    0
     0    0    1    1    1    1    0
     0    0    1    0    1    0    0
     0    0    1    0    1    1    0
     0    0    0    0    0    1    1
se[1]=   3    5    6    2    7    4    1  TC= 2,MC=5,Time=479.860016 sec.
se[2]=   3    5    6    4    2    7    1  TC= 2,MC=4,Time=506.279999 sec.
se[3]=   3    5    6    4    1    2    7  TC= 2,MC=4,Time=506.279999 sec.
se[4]=   3    5    2    6    7    4    1  TC= 3,MC=6,Time=562.000000 sec.
se[5]=   3    5    2    6    4    7    1  TC= 3,MC=5,Time=566.859985 sec.
se[6]=   3    5    2    6    4    1    7  TC= 3,MC=5,Time=566.859985 sec.
se[7]=   3    5    6    7    4    1    2  TC= 3,MC=5,Time=569.859985 sec.
se[8]=   3    5    6    7    4    2    1  TC= 3,MC=5,Time=569.859985 sec.
se[9]=   3    5    6    2    4    7    1  TC= 3,MC=5,Time=569.859985 sec.
se[10]=   3    5    6    2    4    1    7  TC= 3,MC=5,Time=569.859985 sec.
se[11]=   3    5    6    4    7    1    2  TC= 3,MC=4,Time=576.280029 sec.
se[12]=   3    5    6    4    2    1    7  TC= 3,MC=4,Time=576.280029 sec.
 Press any key to continue
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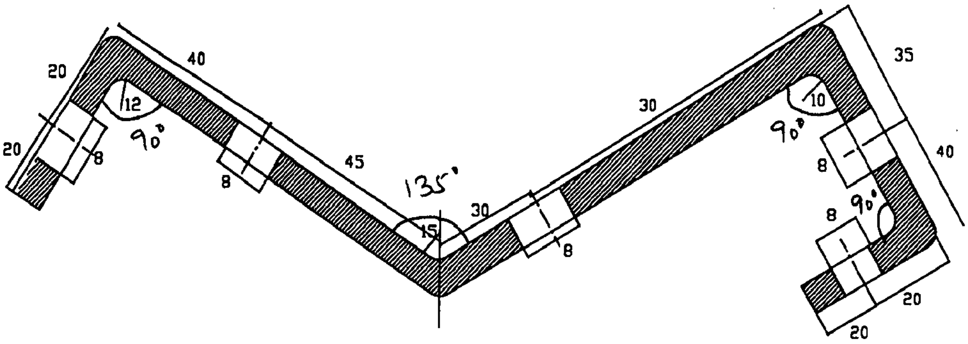
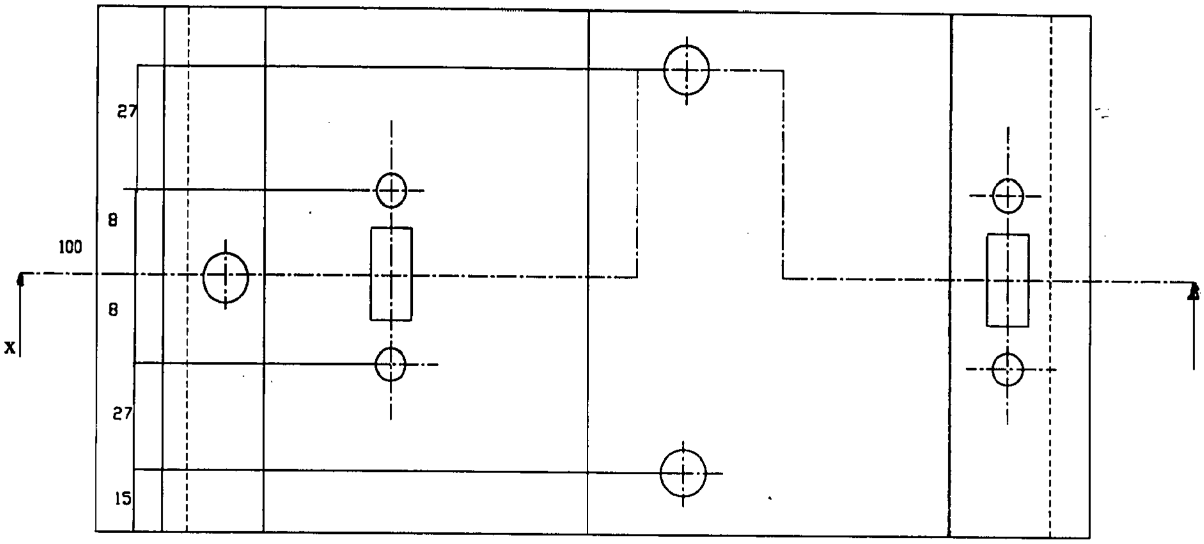
App.-2 [P-1.3]

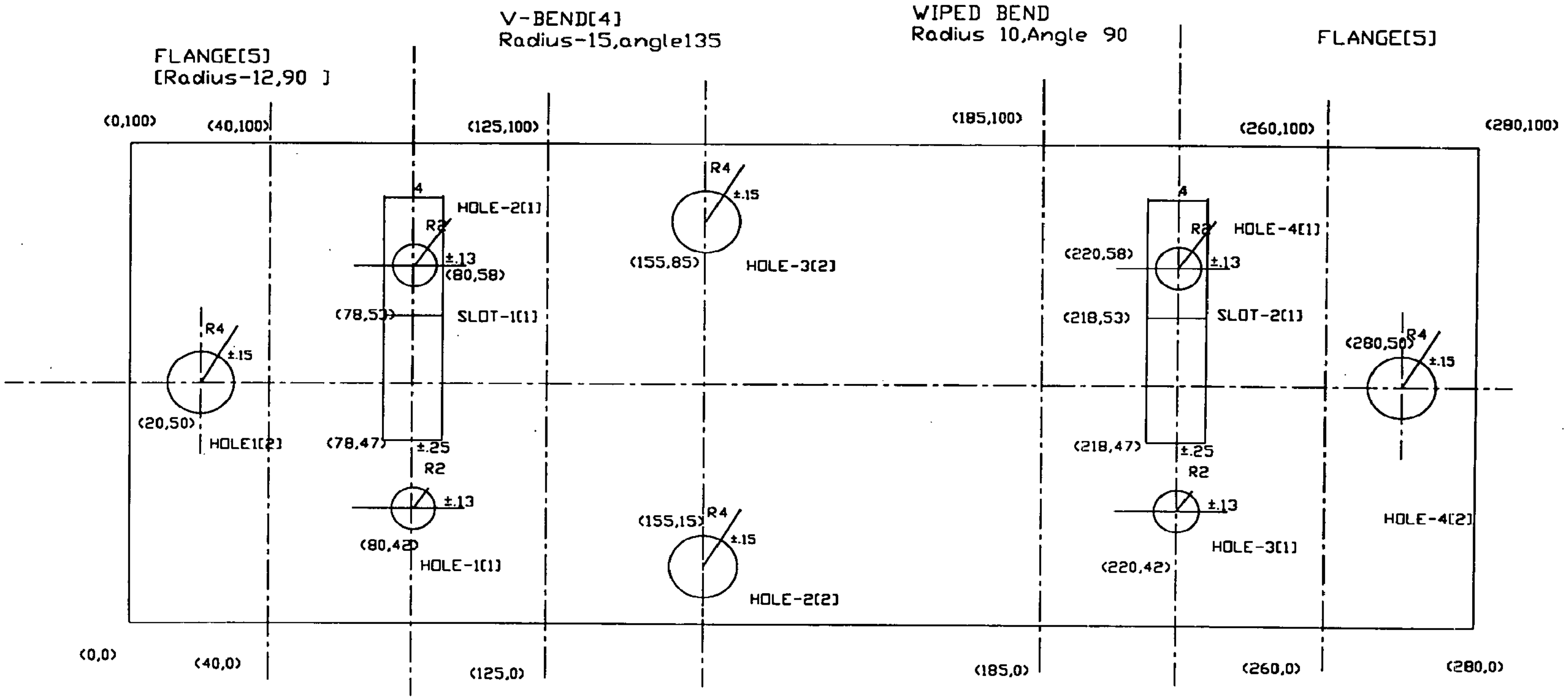


Sectional Elevation on X-Y



Plan

App P2.1 Part-2



App. P-2.2 Operations on the Blank

```
FEATURE RELATIONSHIPS DEVELOPED FOR THE GIVEN FEATURES ARE:-

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    [2] HOLE[4.00]               0   1   0   0   0   1   0

    [3] SLOT[4.00]               0   0   1   0   0   0   0

    [4] BEND[15.00]              1   0   1   1   0   1   0

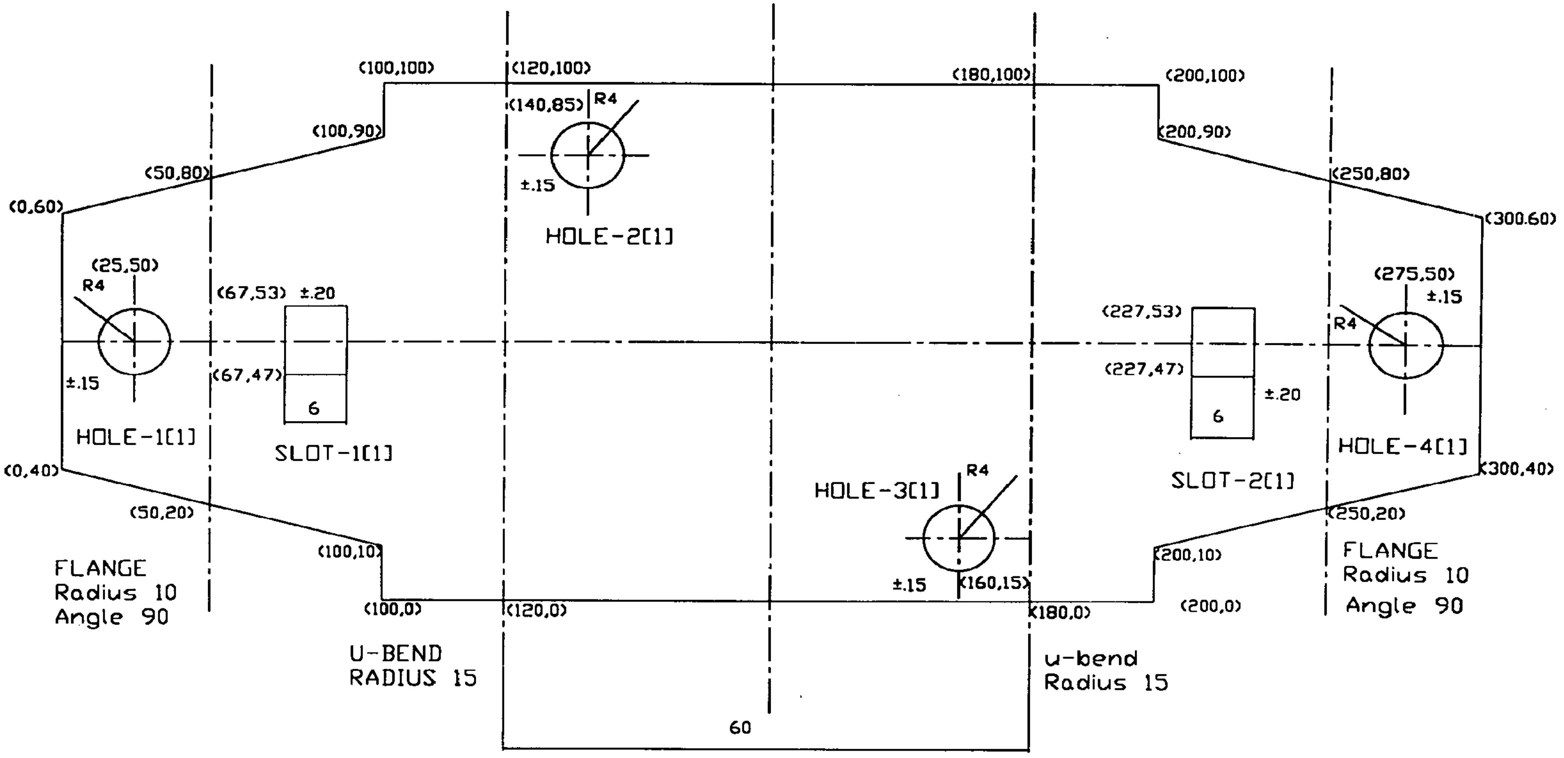
    [5] BEND[10.00]              1   0   1   1   1   1   0

    [6] FLANGE[12.00]            1   0   1   0   0   1   0

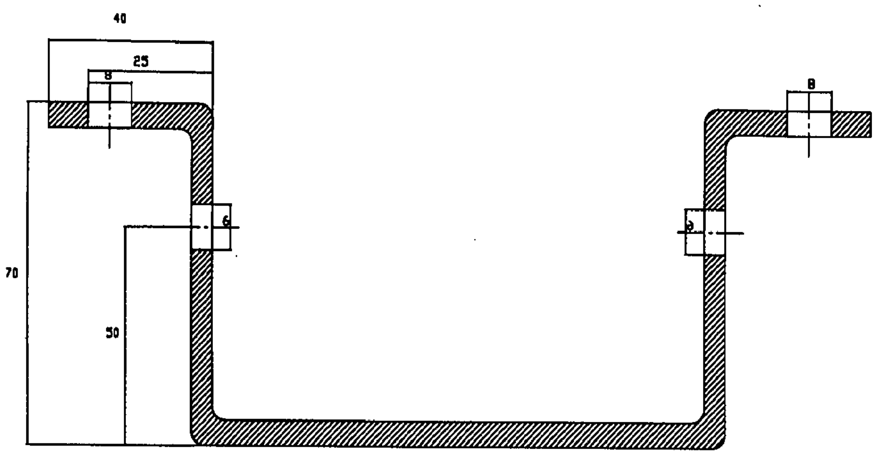
    [7] HOLE[4.00]               0   0   0   1   0   0   1
```

```
   1    0    1    0    0    0    0
   0    1    0    0    0    1    0
   0    0    1    0    0    0    0
   1    0    1    1    0    1    0
   1    0    1    1    1    1    0
   1    0    1    0    0    1    0
   0    0    0    1    0    0    1
se[1]=   3   1   6   4   2   7   5  TC= 2,MC=4,Time=548.419983 sec.
se[2]=   3   1   6   4   7   5   2  TC= 3,MC=5,Time=592.000061 sec.
se[3]=   3   1   6   4   2   5   7  TC= 3,MC=5,Time=592.000061 sec.
se[4]=   3   1   6   4   5   2   7  TC= 3,MC=3,Time=620.000000 sec.
se[5]=   3   1   6   2   4   7   5  TC= 3,MC=5,Time=638.420044 sec.
se[6]=   3   1   6   2   4   5   7  TC= 4,MC=4,Time=710.000061 sec.
 Press any key to continue
```

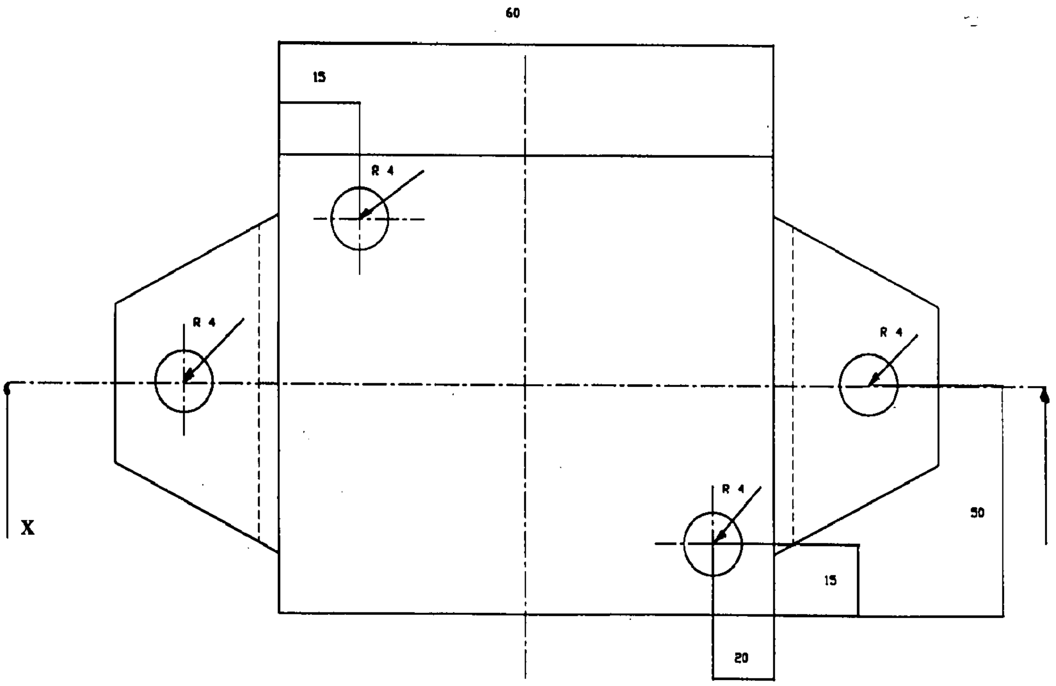
App.2 [P-2-3]



App. P 3.2 Operations on the Blank

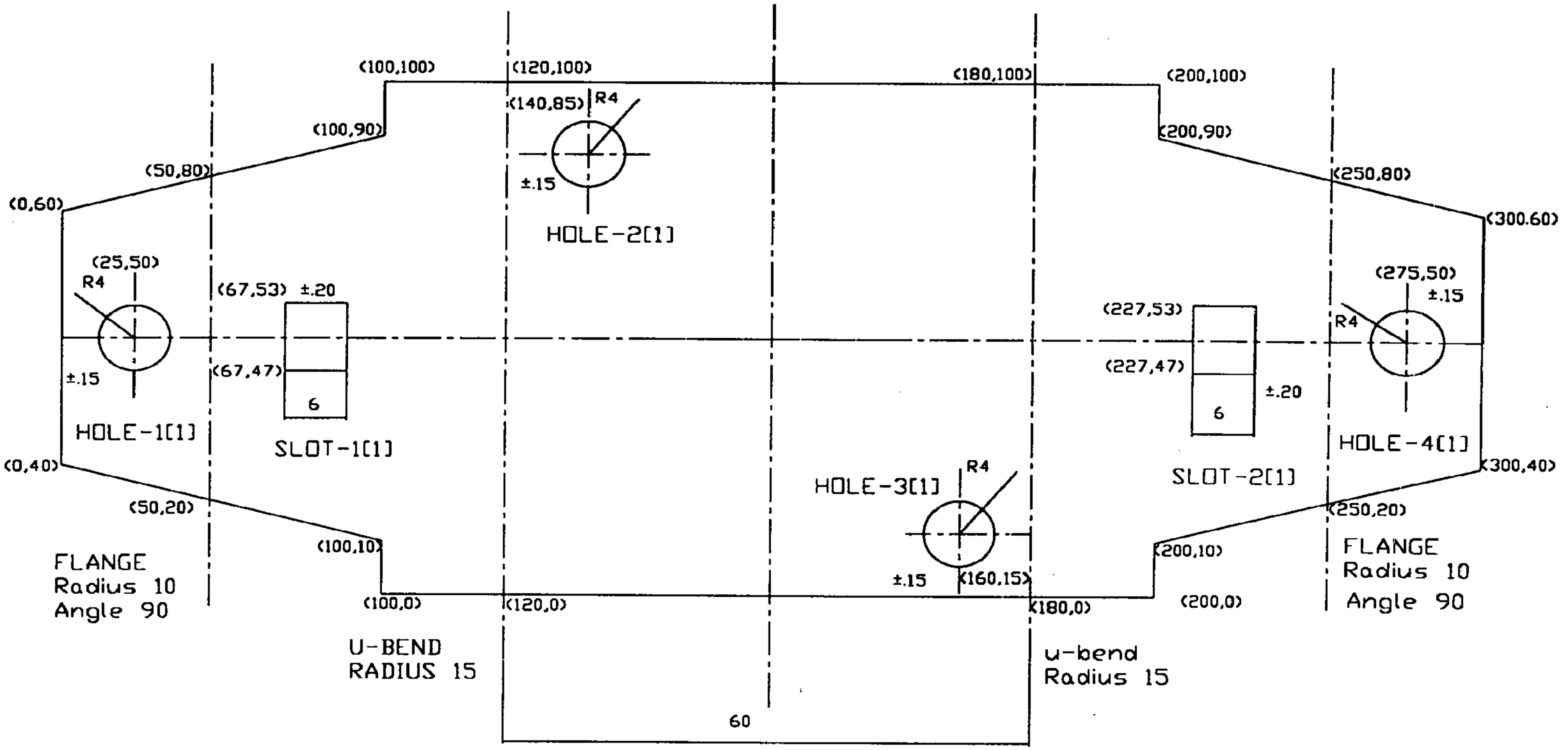


Sectional Elevation on X-Y



Plan

App. P-3.1 Part 3



App. P 3.2 Operations on the Blank

```
 FEATURE RELATIONSHIPS DEVELOPED FOR THE GIVEN FEATURES ARE:-

                                  1    2    3    4    5

[1] HOLE[4.00]                    1    0    0    1    0

[2] SLOT[6.00]                    0    1    0    1    0

[3] BEND[15.00]                   0    0    1    1    0

[4] FLANGE[10.00]                 0    0    0    1    0



[5] HOLE[4.00]                    0    0    1    0    1


   1    0    0    1    0
   0    1    0    1    0
   0    0    1    1    0
   0    0    0    1    0
   0    0    1    0    1
e[1]=   4   2   3   1   5 TC= 2,MC=3,Time=370.999969 sec.
e[2]=   4   3   2   1   5 TC= 2,MC=2,Time=371.000000 sec.
e[3]=   4   3   1   5   2 TC= 2,MC=2,Time=371.000000 sec.
e[4]=   4   1   3   2   5 TC= 3,MC=3,Time=460.999969 sec.
e[5]=   4   1   3   5   2 TC= 3,MC=3,Time=460.999969 sec.


e[6]=   4   2   1   3   5 TC= 3,MC=3,Time=461.000000 sec.
e[7]=   4   3   5   2   1 TC= 3,MC=2,Time=461.000000 sec.
e[8]=   4   3   1   2   5 TC= 3,MC=2,Time=461.000000 sec.
e[9]=   4   1   2   3   5 TC= 3,MC=3,Time=461.000000 sec.
```