CHAPTER 3

REVIEW OF LITERATURE IN SHEET METAL DRAWING

The process of investigation starts with an experimental study from which an analytical model can be developed. The understanding of deep drawing process depends largely on trial and error process. Early researchers measured the changes in thickness undergone by a uniformly thick blank when drawn into a cup and tried to predict the draw forces. Hill, R. (1950) analysed the pure radial drawing of an annular flange assuming a rigid plastic material. He considered plane strain and plane stress cases. Frictional forces were considered negligible and the material was taken to be isotropic. The Tresca yield criterion was assumed with the Levy-Mises flow rule. He concluded that the generalized strain to be taken to be equal to the circumferential strain in the flange. He showed the positions of the particles in the deforming flange and proved that there was little dependence on the stress-strain properties of the material. There were greater tendency of work hardening and reduction of thickness of material across the annulus at any moment. Chung S.Y. and Swift H.W. (1951) extended the work to consider the friction at the rim of the blank. Their assumptions were justified by detailed comparison with their experimental work. Swift’s work led to a good understanding of radial drawing and to an appreciation of thinning of material as it passes over the die. Swift H.W. (1951) reported punch load for different travel positions of punch. Limiting draw ratio was not predicted in their work. The early works in deep drawing has been summarized by Alexander J.M. (1960). Helpful interpretations of Chung S.Y. and Swift H.W. (1951) are found in the works of Hessenberg W.C.F. (1954) and Willis J. (1954).
3.1 METAL FLOW IN DEEP DRAWING

Although the work of Swift assumed that the material was isotropic, it was well known that the sheet material, in particular, could be strongly anisotropic. Lankford W.T. et al (1950) recognized the importance of the variation of \( r \)-value with orientation in the plane of sheet for commercial low carbon steel. Lankford W.T. reported that the variation in \( r \)-values could be exploited for unsymmetrical stampings. Whitely R.L (1960) reported that the preferred orientation is the most important material variable influencing the performance of ordinary ductile metals in cylindrical cup drawing with a flat-headed punch. Whitely R.L. (1960) concluded that the limiting drawing ratio increased as the \( r \)-value of material increase. There were several theoretical studies of the limiting drawing ratio on \( n \)-value and \( r \)-value. In most of the cases failure was assumed to occur by necking under plane strain tension where the punch profile radius joins the straight punch stem. Yamada. Y (1961) reported that the maximum radial drawing load is equal to load necessary to cause necking in plane strain tension in material on punch stem at the limiting draw ratio. El-Sebaie M.G. et al (1972) reported the effect of theoretical results of \( n \) and \( r \) on the limiting draw ratio when drawing with flat headed punch. He concluded through experiments that \( n \)-value has little effect on limiting draw ratio and while increasing \( r \)-value increases the draw ratio. Mellor. P.B. et al (1978) suggested that it was easier to estimate a yield locus and behaviour of metal under tensile and compressive conditions and incorporated the basic information into analysis of sheet metal forming processes.
3.2 DEFORMATION BEHAVIOUR

The deformation behaviour of sheet metal under the conditions of combined stress was investigated by Tozawa Y. (1978). He studied the hardening behaviour of four different materials in the strain range upto 0.1 with the proportional loading path. Darendeliler H. et al (1991) developed finite element method to study elasto-plastic deformation in the presence of large strain and displacements. The work hardening characteristics of the material and Coulomb friction between sheet metal and punch were considered with a constant blank holding force.

Yang D.Y et al (1990) used a method of initial trial generation with geometrical non-linearity combined with contact treatment. By combining the developed contact treatment and the non-linear elastic finite element, an initial trial displacement field was generated. The results compare well for the hemispherical punch stretching with the circular blank.

A systematic approach of energy method was proposed for the analysis of three dimensional sheet metal forming of non-circular cups. Yang D.Y. and Lee H.S. (1993) suggested that deformation region can be divided into several zones by considering geometric characteristics and contact boundary conditions. An elliptical punch was used and experimental results were compared with computed results and found to be in good agreement with experimental value for the punch load and thickness strain distribution.

3.3 ANALYTICAL METHODS

The development of reliable analytical procedures to predict the behaviour of sheet metal deformation processes encountered serious obstacles, like the non-linearity of material properties, unsteady nature of process, large magnitude of
strains, friction effects at tool interfaces. These constraints make the study of the deformation process vary complex requiring larger computational facilities.

Analytical treatments of deep-drawing follow well-known idealized plasticity methods like slab analysis, homogeneous work, slip line field analysis, upper bound techniques and finite element method. Idealization, while providing a better understanding of the process, is applicable to only a limited number of variables. The empirical rules are used for cases where theoretical predictions do not satisfactorily agree with experimental evidence.

Process modelling applied to press working operations is concerned with deriving formability limits analytically thereby providing theoretical insight into metal flow patterns within the deformed zone.

However, the finite element procedure has the unique feature of permitting the user to follow the deformation path from the initial stress free state. It can be applied to problems involving complex geometries and can give detailed stress-strain distribution. The number, shape of the finite elements, solution of deformation increment, iteration criterion and calculation of equivalent strain influence the solution.

From the earlier works on metal forming analysis, two approaches have emerged—the `flow approach`, and the `solid` approach. In the first one, the metal is treated as a non-Newtonian fluid, where as in the second method, the material is assumed to behave like an elasto-plastic or rigid plastic solid. Numerical algorithms of forming processes with various levels of complexity and accuracy were studied in the last three decades resulting in a large number of research findings. Conference proceedings from IDDRG meetings and TMS symposium on NUMIFORM provide a good survey of early works in this area. Although the development of Finite Element Method started in early 1950's, its application to
metal forming processes began only in 1960's, when Yamada Y. et al (1968) introduced closed form of plasticity matrices with elasto-plastic model.

During the last ten years, a number of finite element analysis for modelling sheet metal forming processes have been reported in the literature. Based on the constitutive laws the analysis may be of elastic-plastic type or rigid plastic type.

In the elastic-plastic type, the linearity assumption in stress-strain relation leads to a system of incrementally linear equations amenable to direct solution technique for calculating nodal displacement rates and strain rates. Sheet metal forming processes involve both material and geometric non-linearities, the step size required for an accurate integration is necessarily small. The finite element stiffness equations are non-linear for the rigid plastic formulation.


analyze axisymmetric elastic plastic solids at large strains including deep
drawing with a hemispherical headed punch. A variation in die profile was
attempted in the analysis. The material was assumed to be isotropic and the
computational time was reported to be high.

Albrecht P. Stalman (1985) and Kjell Mattisson et al (1985) used finite
element method for numerical simulation of deep drawing of axisymmetric
components. The sheet metal undergoes bending, unbending and stretching
under punch and die. The majority of the work in the numerical analysis of sheet
metal forming operations is based on simple membrane-shell theory which
neglects the bending effect.

Wang N.M. and Tang S.C. (1988) reported a finite element analysis of
stretch draw of sheet metal over the die corner radius based on shell theory. They
concluded that for axisymmetric punch stretching and cup draw with typical tool
radii, the effect of bending on the calculated strain appears to be small a
correction factor over the membrane solution. The application of finite element
to deep drawing problems with non-linear plasticity was reported by Kobayashi

The implementation of the 3-D finite element method of sheet metal
forming progressed rather slowly. The major obstacle was defining the arbitrary
suitable for representation of any tool surface which relies on described tool
position data. The new method considers a rigid-viscoplastic with the surface
deep drawing process with special emphasis on workpiece geometry. The
process was simulated with FEM using rigid-plastic model with quadratic
element. The model was validated experimentally.
Sukhomlinov L.G. et al (1992) have reported a computational procedure for the analysis of sheet metal drawing with rigid viscoplastic material characterization approach based on flow theory. The non-linear effects due to change in sheet geometry and contact conditions during each increment steps were taken with an iterative solution. The analytical results were compared with experimental values on the strain distribution.

A finite element method to analyse large deformations of thin sheet metal was reported by Onate, E. et al (1983). The formulation was based on visco plastic theory for continuum problems to deal with thin shells. Numerical results of the deep drawing of circular sheets were compared with experimental data and found to be in good agreement for punch load and strain distribution.

An algorithm to model the contact, with friction, between deformable body and rigid surfaces was reported by Pasquinelli, G. (1995). The model integrates the equation of motion in actual reference frame. The model has been implemented in finite element code suitable for dealing with finite deformation problems. The numerical results were compared with experimental values and reported to be in good agreement with punch load at friction condition of 0.2.

Recent developments in finite element analysis include the generation of an increasing number of element formulations. These elements were applied to finite strain problems. Galbraith, P.C. et al (1995) reported the cost benefit relationship of the seven four noded shell elements provided in L.S. Dyana 3-D for sheet metal forming. Strain prediction and drawing force evaluation were reported. A comprehensive analysis was reported for the reliable predictions for strain and draw force for the different element types.

An elastic-plastic deformation history was modelled by Sith G.C. et al (1991) for the analysis of cylindrical cup drawing and concluded that the
maximum of minimum strain energy density would correspond to the regions that undergo large volume change.

Mathematical models of complex forming processes with generally shaped tools are highly non-linear due to large strains, plastic flow and non-linear frictional contact conditions. Michal J. Saran et al (1990) developed a formulation for numerical simulation of complex forming with special emphasis on draw accuracy and computational efficiency. An incremental displacement approach based on Lagrangian formulation with elastic visco plastic material model was attempted. Michal J. Saran concluded that strain distribution agrees with the experimental values.

Guo. Y.Q. et al (1990) developed a finite element algorithm to predict the strain distribution based on inverse approach of sheet metal drawing. Optimization of initial blank contour and the influence of friction force under punch and blankholder were reported. Sosnowski. W et al (1992) made comparative study on sheet metal forming process with numerical study with viscous shell approach and experimental validation. Punch load and thickness strains reported to be in agreement with experimental values.

3.4 EFFECT OF FRICTION

Friction and lubrication are important in the metal forming operations. A model based on the penalty method for 3-D contact problems with friction was reported by Djordje Peric et al (1992). A more reliable and efficient numerical algorithm was suggested by them, which can accommodate the continuous change of the direction and sign of frictional force.
Gelin J.C. et al (1989) developed an algorithm for modelling sheet metal forming with large strain which included the effect of friction between punch and die and sheet interface.

3.5 STRAIN MEASUREMENT TECHNIQUE

Experimental strain analysis in sheet metal forming is done by marking a grid pattern of known dimension on the flat blank and measuring the grid pattern after the deformation. In order to determine the validity of the analytical methods in sheet metal forming, it is necessary to compare the results with experimental validation. In this connection experimental strain analysis can be used to evaluate the strain which can be used to check the adequacy of die design and causes for failure during initial production run. The plasticity analysis should be done on an incremental basis. The incremental strain measurement can be made on forming part in many small steps and measuring the grid changes.

3.5.1 Circle Grid Analysis

The circle grid analysis is used to identify the causes of localized necking and fracture. A circle marked on the flat blank, deforms to an ellipse of major and minor axes. The results are compared on the forming limit diagram obtained for particular material to determine the relative positions of the measurement against the forming limits. This method will provide the information of the closeness of the failure zone in formability diagram.

A variety of grids used for sheet metal forming includes circle, square or combination of both with different dimensions. The grid can be prepared using standard photo resist method. A review about the techniques of photo griding has been reported by Vogel J.H. and Lee. D (1990).
A circle marked on the flat blank, deforms to an ellipse of major and minor axes, \( d_1 \) and \( d_2 \) as shown in Figure 3.1. Assuming proportional deformation, the principal directions are coincident with major and minor axes. The principal elongations are

\[
E_1 = \frac{(d_1 - d_0)}{d_0} \quad (3.1)
\]

\[
E_2 = \frac{(d_2 - d_0)}{d_0} \quad (3.2)
\]

and the principal natural strains, assuming incompressibility are

\[
\varepsilon_1 = \ln \left( \frac{d_1}{d_0} \right)
\]

\[
\varepsilon_2 = \ln \left( \frac{d_2}{d_0} \right)
\]

The process in which \( \varepsilon_2 = \beta \varepsilon_1 \) represents proportional deformation

i) In equal bi-axial tension if \( \beta = 1 \), the circle increases uniformly in diameter. The thickness strain is twice the surface strain and this process is referred as pure stretching.

ii) If the circle elongates in one direction when \( \beta = 0 \), the strain path lies on the major strain axis and this is a plane strain process.

iii) A circle that extends in one direction and shrinks transversely so that \( \beta = -1 \), then

\[
\varepsilon_1 = -\varepsilon_2
\]

This is called pure drawing and is shown in the Figure 3.2.
FIGURE 3.1 DEFORMATION OF A CIRCLE TO AN ELLIPSE IN A HOMOGENEOUS FIELD

FIGURE 3.2 GRAPHICAL REPRESENTATION OF PURE PROPORTIONAL LARGE DEFORMATION IN THE TWO-DIMENSIONAL STRAIN SPACE
The circle grid method is very convenient for finding out the strain at a point in sheet metal part. If the technique is used incrementally it will indicate whether the principal strain ratios are in constant proportion.

The circle-grid strain analysis has been used in the large-strain zone, where plastic instability or fracture are important. Warren, R. et al (1984) reported that grid circles less than 5 mm diameter were suitable for strain measurement. Ishigaki H. (1978) suggested scribed circle-method using larger circles of 40 mm diameter.

Sowerby R. et al (1981) demonstrated that the determinations of plastic strains may be simplified if a particular, idealised deformation mode is assumed. In the circle grid strain measurements, the material element within one circle is subjected to pure homogeneous deformation. The major and minor axes of the deformed ellipse determine the principal strain. This condition exists for pure coaxial deformation of material element.

3.6 SCOPE AND OBJECTIVES OF THE PRESENT WORK

Without adequate knowledge of the influences of the variables such as contact friction, material properties and the work piece geometry on the process mechanics in deep drawing, it would not be possible to design the dies and the other process equipment’s to prevent the occurrence of defects and optimise the process. In the past, several approximate methods of analysis were developed and applied to various forming processes. Amongst the commonly used methods, the finite element method is widely used in recent times for the process simulation of deep drawing.
The present research work is focused on

i) Analytical modelling and process simulation to predict the effect of parametric variations in deep drawing process.

ii) Experimental validation of the analysis and comprehensive parametric study of the deep drawing process with different material conditions.