CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

The main purpose of this work is to study the capacity and conditions of a metal during the formation and deformation processes. In metal forming operations, the metals are subjected to three different strain conditions; namely, biaxial stretching, plane strain and deep drawing. In biaxial stretching, thinning of sheet takes place and both the principal stresses are tensile in nature. Biaxial stretching involves both principal stresses as tensile in both directions, whereas deep drawing involves tensile stress in one direction, and the compressive principal stress in the other direction, and is measured by a stretch test using a hemi-spherical punch. The plane strain condition is formed, when one principal stress is in the neutral condition. The ability of deep drawing is assessed by the swift cup test and has some constraints. The drawing ability improved significantly when a metal is drawn to a die having a wide entry section. For evaluating the forming limit diagrams (FLD) the results from the three strain conditions are combined.

The formability of sheet metal can be defined by plotting the FLD. It is influenced by material properties and their constraints. Some of the constraints are the frictional factor, working temperature, annealing, and initial texture condition. The two general failure modes of the sheet metal drawing process are fracture and wrinkle. The fracture and material void behaviour are influenced by the strain condition. The formation of the
crystallographic texture on the initial material condition also influences the formability of the sheet metal.

Characterization and modelling the behaviour of the formability of the sheet metal, is of much industrial importance and can be considered as a futuristic work. Also the incorporation of reliability in formability studies, is of prime concern in quality assessment. The present study is undertaken to evaluate the formability of commercially pure aluminium grades of sheet metal through the study of tensile property, formability property, forming limit diagrams, void coalescence property and texture analysis, with the help of the modelling tool, response surface methodology and statistical tools; the first order reliability method and the Monte Carlo simulation method. The materials used for this analysis are Aluminium alloys, which play a major role in determining the modern Engineering Materials. Hence, they are important materials, because of their various desirable properties, availability and wide application.

1.2 DESIRABLE MATERIAL

A material possessing desirable properties is the modern trend in engineering application. Light weight, formability and strength are the important desirability properties opted by the designer in the selection of a material for most of the modern engineering applications. Aluminium and its alloys are preferred by designers for their light weight applications. Aluminium alloys, vary by their tensile properties, formability properties and surface characteristics from one another at different dimensions, annealing temperatures, duration of annealing and mode of cooling, composition and percentage of initial strain. Most of the components are manufactured by the forming process, and hence, the outcome of the formability analysis of aluminium with its alloys, will be a useful input for the designing and manufacturing of modern engineering components. Broad research on their
formability aspects is necessary, to develop constructive components of complex shapes (Venkateswarlu et al 2010).

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1.3 SHEET METAL FORMING

Sheet metal forming, an important type of metal forming processes, uses sheets to produce desirable components or products. In sheet metal forming, force is applied to a piece of sheet metal to modify its geometry rather than remove any material. The applied force and stress on the sheet metal beyond its yield strength, causes the material to plastically deform, but without failure. As a result, the sheet can be bent or stretched into a variety of complex and required shapes. The force is applied on metal blanks using tools, punches and dies. Sheet metal forming processes include bending, stretching, stamping,…etc. The forming operations of sheet metal include various types and conditions of strains, which can be significantly evaluated to predict the properties of the metal and its forming limit (Narayanasamy and Sathiya Narayanan 2006).

Preferably, the forming operation is done in most of the engineering applications, which require annealing procedures, microstructure examination, characterization of the sheets and their relations to attain higher formability (Xing et al 2001). The characterization involves the experimental determination of the microstructural aspects, tensile properties and formability parameters such as average plastic strain ratio and planar anisotropy (Takuda et al 1995). The press-forming applications have been
examined to find the suitability of the deformed aluminium alloy sheets in stamping applications (Ravi Kumar and Swaminathan 1999).

The common problems faced by the manufacturer in sheet metal forming are given in the following section.

1.4 PROBLEMS IN SHEET METAL FORMING

Major sheet metal forming problems are fracturing, buckling, wrinkling, selection of sheet thickness shape distortion, and loose metal and undesirable surface texture. Fracturing occurs in sheet metal forming when the strain exceeds a critical value, and is considered as a factor determining the fracture limit diagram. Uniform deformation, localized thinning (a band known as neck) and fracture are the stages during the progressive deformation of the sheet metal. Effect of sheet thickness on formability is the recent study (Anil kumar et al 2010, Rahavan et al 2010). In order to avoid these metal forming problems, the results of sheet metal testing are essential for formability studies.

1.5 TESTING OF FORMABILITY

The term formability, in sheet metal forming is used to indicate the ability of the metal to adopt ease deform. Formability can be quantitatively estimated by the strength, characteristics and resistance to failure, the formability indices. Based on the forming operation, the techniques used to measure the formability vary. In the study, sheet metal and its forming Limit Diagram (FLD) are used to quantify the formability. The major strain and minor strain are the limits of magnitude of either localized thinning or necking prior to fracture. The hemispherical punch is used in the experiment to find forming limit diagram. By changing the friction condition and test blank widths, the strain path and the failure strains are varied. There is no single test
which provides an accurate indication of the formability of a material in all situations, as sheet metal forming operations are so diverse in nature (Stefan Holmberg et al 2004). Most of the automotive outer body panels are formed by the stretching of the sheet metal (Ravikumar and Gupta, 2006). In Plane-strain stretching, elongation occurs in one direction, whereas in the perpendicular direction no dimensional change occurs. The tensile stresses acting in a perpendicular direction to the plane of the sheet cause stretch forming (Ravikumar et al 2007). Deep drawing is another important type of deformation, and it elongates in one direction and compresses in the perpendicular direction. Practically, the majority of sheet metal forming operations are subjected to a combination of different types of forming, which can be evaluated by Formability tests.

1.5.1 Formability Tests

Formability tests are of two basic types: namely, intrinsic and simulative. Intrinsic tests measure the basic properties of the materials that can be related to their formability. Simulative tests are tests in which the sheet metals are subjected to deformation, that closely resembles the deformation that occurs during a particular forming operation.

Properties which are insensitive to the thickness and the surface conditions of the materials are measured using intrinsic tests, whereas properties which are sensitive to thickness, surface condition, lubrication, geometry and type of tooling are measured, using simulative tests. The Olsen and Swift cup test are examples of simulative tests. The information provided by the simulative tests usually relates to only one type of forming operation. The uniaxial tensile test is an important intrinsic test, which provides many material properties for different metal forming operations (Waleed et al 2007, Stefan Holmberg et al 2004). The plane-strain tensile test, the Marciniak stretching and sheet torsion tests, hydraulic bulge test, the Miyauchi shear test
and hardness tests are some of the intrinsic tests which indicate the formability. As the result of the formability test, forming limit diagrams can be plotted for predicting the material properties.

1.6 FORMING LIMIT DIAGRAM

The Forming Limit Diagram is a tool to indicate the limiting strains that a sheet metal can sustain for various major to minor strain ratios, which are equivalent to various secondary metal forming processes, ranging from stretch forming to deep drawing. Two types of laboratory tests, are used to evaluate the forming limit diagrams, namely, hemispherical punch method and in-plane determination. The hemispherical punch method involves stretching the test specimens over a punch. This produces some out-of-plane deformation, but the second test produces only in-plane deformation, and does not involve any contact with the sample within the gauge length. The hemispherical punch method has been more widely used (Siguang Xu and Weinmann 2000, Matin and Smith 2005, Chamanfar and Mahmudi 2005 and Raghavan and Garrison 2010) than in-plane determination. The in-plane determination provides slightly different results (Barlat 1987).

1.6.1 HEMISPHERICAL PUNCH METHOD

In this method, test blanks with varying widths are clamped in a die ring, and formed by a hemispherical punch (Narayanasamy et al 2009) up to fracture. As the blank width is varied, various strain ratios are achieved. The strains are measured in and around the necking and fracture regions. The forming limit curve is drawn above the strain value measured outside the necked regions, and below the strain value measured inside the necked and fractured regions.
1.6.2 In-Plane Determination

The in-plane determination of the forming limit diagram can be achieved using the uniaxial tensile test, rectangular sheet tension test (or) Marciniak biaxial stretching test with elliptical and circular punches. The forming limit curve can be determined over the full range of strain ratios without introducing any out of plane deformation. While comparing the in-plane and punch methods, close agreement is achieved for a negative strain ratio, whereas, the punch test shows slightly higher values for the plane strain and for positive strain ratios (Holger Aretzm et al 2007).

Based on recent works (Benzerga et al 1999, Narayanasamy et al 2006, 2009), void study can be correlated with these formability studies and they are given as under.

1.7 VOID COALESCEENCE

The ductile material models accounting for the nucleation and growth of voids are discussed by many researchers (Arild et al 2004, Wang et al 2004), and the parameters studied from the behaviour of materials are considered as void parameters or void coalescence properties. Such studies have been used to investigate the nucleation of voids and void coalescence, as well as the interaction between different sizes and scales of voids. The parameters, namely, void size, void area fraction, d- factor, L/W ratio and ligament thickness, are the subject of interest, which are investigated in the later part of this section. The Scanning Electron Microscopy (SEM) images are analyzed by Auto CAD software to predict the various parameters. These parameters can be correlated to the formability properties. The parameters tested by Narayanasmay et al (2009) will form a useful methodology and can predict better results in sheet metal formability. The crystallographic study
has its due impact on the study of formability and the relevant works are still in progress.

1.8 CRYSTALLOGRAPHIC TEXTURE

A crystal is characterized by the periodic arrangement of its elements (atoms, ions) in space. In the field of material science and engineering, the distribution of the crystallographic orientations of a polycrystalline sample is called as texture. If these orientations are fully random in a sample, it has no texture. If the crystallographic orientations have some preferred orientation, but are not random, then the sample has different textures, namely, weak, moderate and strong. The crystal having the preferred orientation and its degree is dependent on the percentage (Bennett et al 2009). Texture can have a great influence on the material properties and is seen in almost all engineered materials. Anisotropy is a dependence of the crystal properties in the chosen direction. The anisotropy of a polycrystalline material significantly depends on the preferred orientations of the bounded crystallites. There are two boundary cases: If all crystallites have the same orientation, the anisotropy of the polycrystal exactly equals that of the single crystal (Engler and Randle 2009). In an isotropic texture, all orientations occur with the same probability; the behavior of the polycrystalline material is isotropic even though every single element (crystallite) shows an anisotropic behavior (Engler et al 2001). Texture can be analysed through the following methods.

1.8.1 Crystallographic Texture analysis

Texture can be determined by various methods, namely, a quantitative analysis and a qualitative analysis. In quantitative techniques, the most widely used is X-ray diffraction using texture goniometry, which is followed by the electron backscatter diffraction (EBSD) method in Scanning Electron Microscopes. Simple X-ray diffraction or the polarized microscope
is used for the Qualitative analysis through Laue photography. Neutron and synchrotron high-energy X-ray diffraction allow access to textures of bulk material analysis, but a more appropriate method for analyzing thin film textures is the use of laboratory x-ray diffraction instruments (Samajdar et al 2001).

Often texture is represented using a pole figure, in a stereographic projection, a specified crystallographic axis (or pole) from each of which a representative number of crystallites is plotted, along with the directions relevant to the material’s processing history. These defined directions are called as a sample reference frame. The investigation of textures started from the cold working of metals, usually referred to as the rolling direction, RD, the transverse direction, TD and the normal direction, ND (Matthies et al 1988).

1.8.2 Common Textures

The commonly found textures in processed materials are cube(001)<100>, brass(110) <-112>, copper (112)<11-1> and S(123)<63-4>(Lademo at al 2008). They are named either by the material they are most found in, or by the scientist who discovered them. These are given in miller indices for simplification purposes as given in the following sections.

1.8.3 Orientation distribution function

The full 3D representation of a crystallographic texture is given by the orientation distribution function, which can be achieved through the evaluation of a set of pole figures or diffraction spectra. Subsequently, all pole figures can be derived from the ODF. The ODF is defined as the volume fraction of grains with a certain orientation. The orientation is normally identified using three Euler angles. The Euler angles then describe the transition from the sample’s reference frame into the crystallographic
reference frame of each individual grain of the polycrystal (Matthies et al 1988).

The orientation distribution function cannot be measured directly by any technique. Traditionally both X-ray diffraction and EBSD may collect pole figures. Some represent the ODF as a function, a sum of functions or expand it in a series of harmonic functions (Pedersen et al 2008). Others, known as discrete methods, divide the ODF space in cells and focus on determining the value of the ODF in each cell.

1.8.4 Origin

In a fiber, all crystals tend to have a nearly identical orientation in the axial direction, but nearly random radial orientation. Single-crystal fibers are also not uncommon. The making of metal sheet often involves compression in one direction and, in efficient rolling operations, tension in another, which can orient crystallites in both axes, by a process known as the grain flow. However, cold work destroys much of the crystalline order, and the new crystallites that arise with annealing usually have a different texture (Engler and Randle 2009). The control of texture is extremely important in the making of a silicon steel sheet for transformer cores (to reduce magnetic hysteresis), and of aluminium cans (since deep drawing requires extreme and relatively uniform plasticity) (Engler and Lucks 1992).

These results of the formability studies through the Forming limit, void study and texture analysis are suitable for analyses through response surface methodology (RSM).
1.9 RESPONSE SURFACE METHODOLOGY

In statistics, response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. The method was introduced by Box and Wilson in 1951. The main idea of the RSM is to use a sequence of designed experiments to obtain an optimal response. Box and Wilson suggest using a second-degree polynomial model to do this (Vaughn et al. 2007). They acknowledge that this model is only an approximation, but use it because such a model is easy to estimate and apply, even when little is known about the process. It has the following design and approach in modeling (Alimkaddem et al. 2007).

1.9.1 Basic Approach

An easy way to estimate a first-degree polynomial model is to use a factorial experiment or fractional factorial designs. This is sufficient to determine which explanatory variables have an impact on the response variable(s) of interest. Once it is suspected that only significant explanatory variables are left, then a more complicated design, such as a central composite design, can be implemented to estimate a second-degree polynomial model, which is still only an approximation at best. However, the second-degree model can be used to optimize (maximize, minimize, or attain a specific target for) a response (Anderson and Whitcomb 2005).

1.9.2 Central composite design

In statistics, a central composite design is an experimental design, useful in response surface methodology, for building a second order (quadratic) model for the response variable without needing to use a complete two-level factorial experiment. After the designed experiment is performed, linear regression is used, sometimes iteratively, to obtain results. Coded
variables are often used when constructing this design (Prabaharan et al 2010). The design consists of three distinct sets of experimental runs: (a) A factorial (perhaps fractional) design of the factors studied, each having two levels; (b) A set of center points, experimental runs whose values of each factor are the medians of the values used in the factorial portion. This point is often replicated in order to improve the precision of the experiment; (c) A set of axial points, experimental runs identical to the centre points except for one factor, which will take on values both below and above the median of the two factorial levels, and typically, both outside their range. All factors are varied in this way.

1.9.3 Box Behnken Design

In statistics, Box–Behnken designs are experimental designs for response surface methodology, devised by Box and Behnken in 1960, to attain the following goals (Vaughn et al 2007):

- Each factor, or independent variable, is placed at one of three equally spaced values. (At least three levels are needed for the following goal.)

- The design should be sufficient to fit a quadratic model, that is, one containing squared terms and products of two factors.

- The ratio of the number of experimental points to the number of coefficients in the quadratic model should be reasonable (in fact, their designs kept it in the range of 1.5 to 2.6).

- The estimation variance should more or less depend only on the distance from the centre (this is achieved exactly for the designs with 4 and 7 factors), and should not vary too much inside the smallest (hyper)cube containing the experimental points.
For instance, the Box–Behnken design for 3 factors involves three blocks, in each of which 2 factors are varied through the 4 possible combinations of high and low. It is necessary to include centre points as well (in which all factors are at their central values) (Anderson and Whitcomb 2005).

Optimization is the modern approach in engineering application and design of experiment used to improve the effectiveness of the study (Carlos et al 2004).

1.10 OPTIMIZATION OF TEXTURE COMPONENTS USING DESIGN OF EXPERIMENT

In the design of experiments, optimal designs are a class of experimental designs that are optimal with respect to some statistical criterion. In the design of experiments for estimating statistical models, optimal designs allow parameters to be estimated without bias and with minimum-variance. A non-optimal design requires a greater number of experimental runs to estimate the parameters with the same precision as an optimal design (Anderson and Whitcomb 2005). Testing the reliability of the data is inevitable to foot forth into the next generation.

1.11 RELIABILITY ANALYSIS

In statistics, reliability refers to the consistency of a measure. A measure is said to have a high reliability if it produces consistent results under consistent conditions (Kleiber et al 2002). While there are many reliable tests of specific abilities, not all of them would be valid for predicting, say, job performance. In terms of accuracy and precision, reliability or relevant is analogous to precision, while validity is analogous to accuracy (Kleiber 2002).
While reliability does not imply validity, a lack of reliability does place a limit on the tests, overall validity. A test that is not perfectly reliable cannot be perfectly valid, either as a means of measuring the attributes of a person or as a means of predicting the scores on a criterion (Koen Janssens et al 2001). A reliable test may provide useful valid information; a test that is not reliable cannot possibly be valid as shown in Figure 1.1. Some of the common effective methods adopted by recent researchers for reliability in a formability study are discussed as under.

![Diagram indicating relations between Reliability (by relevant reading) and valid reliability.](image)

**Figure 1.1** Diagram indicating relations between Reliability (by relevant reading) and valid reliability.

### 1.11.1 First order reliability

The first-order reliability method, (FORM), is a semi-probabilistic reliability analysis method devised to evaluate the reliability of a system. The first developments of the First Order Reliability Methods, also known as FORM methods, took place almost 30 years ago. Since then the methods have been refined and extended significantly, and by now they form one of the most important methods for reliability evaluations in the structural reliability
theory (Jeong Kim et al. 2006). Several commercial computer codes have been developed for FORM analysis, and the methods are widely used in practical engineering problems.

1.11.2 Monte Carlo simulation

Monte Carlo experiments are a class of computational algorithms that rely on repeated random sampling to compute their results. Monte Carlo methods are often used in computer simulations of physical and mathematical systems. These methods are most suited for calculation by a computer and tend to be used when it is infeasible to compute an exact result with a deterministic algorithm. This method is also used to complement theoretical derivations. Monte Carlo methods are especially useful for simulating systems with many coupled degrees of freedom, such as fluids, disordered materials (Jeong Kim et al. 2006), strongly coupled solids, and cellular structures (see cellular Potts model).

The objective and scope of this work are given below:

1.12 OBJECTIVES AND SCOPE

Among the above-said tests and techniques for the formability of sheet metals, the determination of the forming limit diagram by the hemispherical punch method is effective and gives better results and therefore this is employed in the present work. The present work relates the various annealing temperatures with the mechanical properties, formability void parameters, microstructure, and texture characteristics of commercially pure aluminium grades of sheet metals. This work is aimed,

- To reveal the material properties and their effect on the formability of the sheet metals.
- To study the Mohr's circle shear strain developed under various conditions of strain, and its importance in sheet metal forming.

- To determine the different strain ratios involving the effective strain, and Mohr's circle shear strain, and to establish the relationship between these strain ratios and various factors involving the average strain hardening exponent (n) value and normal anisotropy (r) value.

This work also brings out the correlation between mechanical properties, formability, Void coalescence and texture properties of the aluminium alloy sheets of Al 1350, 8011 and 1145 alloy grade of thickness 1.2 mm, 1.5mm and 1.8 mm respectively.

- To investigate the mode of evaluation of the tensile results, formability results, and void coalescence of commercially pure aluminium of three different thicknesses and three different annealing temperatures using numerical modelling practice.

- To correlate the tensile properties, formability and its parameters and void coalescence parameters using RSM. The annealing temperature, sheet thickness and specimen orientations or width are to be investigated as a function of three independent variables to explore their effects on output responses, using response surface methodology. An attempt is also made to derive a mathematical model for tensile properties, forming limit strains and void coalescence parameters.

- To investigate the mode of evolution of texture components, of commercially available aluminium alloy sheets of three different thicknesses and three different annealing temperatures, using numerical modelling practice.
• To correlate the texture and formability, using RSM. The annealing temperature and sheet thickness are investigated as a function of two independent variables on texture components to explore their effects as output responses, using response surface methodology.

• To combine the results of the experimental investigation with reliability assessment techniques, using FORM and MCS.

1.13 OVERVIEW OF THE THESIS

The thesis is organized in to six chapters and a very brief chapter-wise outline of the thesis is given below:

The present chapter is introductory in nature and presents a general description of sheet metal forming, method of testing, forming limit diagrams, void coalescence study, texture analysis, and reliability analysis. This chapter also deals with the introduction of response surface methodology.

Chapter 2 presents a review of the related literature on forming limit diagrams, different theoretical models for forming limit diagrams, theoretical and experimental forming limit diagrams for different sheet metals, crystallographic texture and reliability analysis of the FLD of sheet metals. Finally, the scope of the research problems is identified and the need for the present study is established. Chapter 3 deals with the experimental investigation of the tensile test, forming limit diagram and void parameters in the blanks under different strain conditions. The experimental investigation of fractography and texture of the sheet metals are also dealt with in this chapter. Chapter 4 deals with the theoretical analysis of the present research work. This comprises the theory of plasticity, instability criteria, evolution of texture, pole figure path, response surface methodology, power transform,
residual plot and statistical analysis, using the first order reliability method and Monte Carlo simulation.

Chapter 5 presents and discusses the results of various experiments carried out in this research work. Chapter 6 is the concluding chapter in which the major contributions of the research study are highlighted. Guidelines for future work are also included in this chapter. The references to the literature relevant to the present research are reported at the end of this thesis.