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Experimental Determination of Anisotropic Properties and Evaluation of FLD for Sheet Metal Operations*

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Abstract. Most of the sheet metals, in general exhibits a high an-isotropic plasticity behaviour due to ordered orientation of grains due to the cold rolling process. This results in an uneven deformation such as ears in deep drawing operation. This paper is focused on various deformation models, determination of sheet metal yielding and an-isotropic properties, limit strains and construction of FLD.

Keywords: Sheet metal · Normal anisotropy · Planar anisotropy · LDR

1 Introduction

Due to various issues concerned with environmental pollution and scarcity of petroleum, the automobile industry is forced to reduce the weight of the vehicles, replacing heavier materials with lighter ones, viz, aluminium, magnesium and advanced high strength steels. The optimisation of sheet metal forming process becomes crucial importance, for articles manufactured various industries such as automotive, aerospace, building, packaging and electronic industries.

The an-isotropic property and forming-limit-diagram studies are essential for sheet metals for quality forming. The plastic deformation of blanks during a forming process are quantified through formability. The formability of a sheet metal is limited by the occurrence of flow localisation or plastic instability. The various issues of formability may be monitored by a good understanding of the deformation processes using Forming Limit Diagram (FLD). In recent years, various advanced methods were developed for predicting the forming limits of sheet metal deformed through linear and non-linear strain paths. Much research was carried out in sheet metal forming operations using various methods, viz, experimental methods, analytical methods and computational methods [**?**].

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2 Literature Review

The knowledge of the formability is essential for the success of sheet metal forming operation. The normal anisotropy and FLD is essential tools for study of sheet metal formability. They indicate the capacity of the material for stretching and drawing up to limiting strain value. The forming limit diagram (FLD) introduced by Keeler (1965), and Goodwin (1968) is a constructive concept for characterising the formability of sheet metal. It has proved to be an essential tool for material selection, design and try out of the tools for deep drawing operations. Sheet metal forming processes often imposes forming sequences in severe strain-path changes that drastically influence the forming limits [2]. The deformation mode, loading history and material behaviour are essential factors that affect the maximum admissible strains. For non proportional strain paths to complex loading, the FLDs are very much useful to understand the behaviour of the material. The estimation of severity of the strain paths of deformation is essential for optimisation of configurations of dies to to avoid neck formation. Due T N et al. [3] proved that the punch-nose-radius has more influence, compared to blank-holder-force and the die-shoulder-radius on improvement of the formability of the blank material. The Marciniak- Kuczinsky (MK) approach [5,6] is one of the most important tools, when the sheet metal containing a region of local imperfection and developing a localised heterogeneous plastic flow, has become one of the most important tools for predicting the sheet metal formability. The predicted limit strains strongly depend on the constitutive law incorporated into the MK analysis [4,5,6,7].

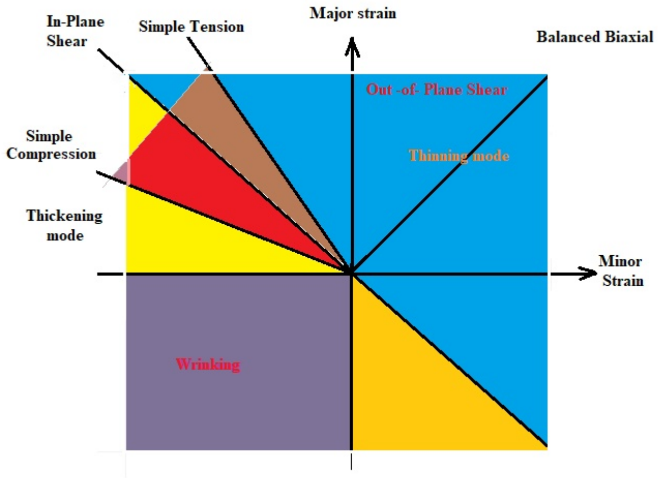

Fig. 1. Typical sheet formability under plane stress condition

3 Constitutive Models for Metal Forming

The determination of yield characteristics for a sheet metal is very important to describe the plastic behaviour of metallic materials for forming processes [8]. In uniaxial state of stress, the point of the yield can be obtained from the stress strain curve. In multiaxial state of stresses, the determination of yield stress becomes a complex and requires an advance flow equations [9]. The yield stress, σ_f (also called flow stress) is simply a stress at which the material yields, or deforms plastically. The yield criteria are equations that incorporate a known value of the flow stress to calculate the stress states necessary for yielding. The Tresca criterion and von Mises criterion are the two important criteria involving complex descriptions of stress state.

3.1 Isotropic Yield Criteria

The plastic yielding in isotropic materials depend on the quantum of principal stresses but not with directions. The most widely used isotropic yield models are the Tresca criterion and the Von Mises criterion.

Tresca yield criterion: The Tresca criterion for yielding is based on the assumption that yielding to occur, when the greatest maximum shear stresses reach to a critical value. It can be written as

$$max\{|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|\} - \sigma_f = 0 \tag{1}$$

Under plane stress condition, Eq. 2 becomes

$$|\sigma_1 - \sigma_2| - \sigma_f = 0 \tag{2}$$

Von Mises yield criterion: The Von Mises yield criterion states that yielding will occur, when the elastic energy of distortion reach a critical value. This criterion for plane stress is in the form

$$\sqrt{\sigma_1^2 - \sigma_1\sigma_2 - \sigma_2^2} - \sigma_f = 0 \tag{3}$$

3.2 Anisotropic Yield Criteria

Hill R has developed several yield criteria for anisotropic plastic deformations. The basic version is the extension of the Von Mises yield criterion and is in quadratic form.

Hill 1948 : For metallic materials, the yielding is independent of pressure in most of the cases, i.e., the hydrostatic pressure has no influence on yielding. For anisotropic materials yielding properties are directional. The simplest form of yield criteria is with respect to a coordinate system associated with the axes of symmetry of the material. Hill proposed an extension of the isotropic Mises criterion to orthotropic materials

$$\begin{aligned}\phi &= F(\sigma_{yy}-\sigma_{zz})^2+G(\sigma_{zz}-\sigma_{xx})^2\\ &\quad +H(\sigma_{xx}-\sigma_{yy})^2+2(L\sigma_{yz}^2+M\sigma_{zx}^2+N\sigma_{xy}^2\\ &= \bar{\sigma}^2\end{aligned} \tag{4}$$

where F, G, H, L, M and N are material constants. This yield function is well suited for specific metals such as steel.

Generalized Hill yield criterion The generalized Hill yield criterion[2] has the form

$$\begin{aligned}&F|\sigma_2-\sigma_3|^m+G|\sigma_3-\sigma_1|^m+H|\sigma_1-\sigma_2|^m\\ &\quad +L|2\sigma_1-\sigma_2-\sigma_3|^m+M|2\sigma_2-\sigma_3-\sigma_1|^m+N|2\sigma_3-\sigma_1-\sigma_2|^m=\sigma_y^m\end{aligned} \tag{5}$$

where σ_i is the principal stress and σ_y is the yield stress, and F, G, H, L, M, N are constants. The value of m is determined by the degree of anisotropy of the material and must be > one for convexity of the yield surface.

For the materials exhibiting orthotropic symmetry Hosford proposed the yield criteria as

$$\begin{aligned}\phi &= F\left|\sigma_{22}-\sigma_{33}\right|^a+G\left|\sigma_{33}-\sigma_{11}\right|^a+G\left|\sigma_{11}-\sigma_{22}\right|^a\\ &= \bar{\sigma}^a\end{aligned} \tag{6}$$

Hosford yield criterion Hosford proposed the following modification of Hill's orthotropic yield criterion.

$$\begin{aligned}&A\sigma_{11}+B\sigma_{22}-(A+B)\sigma_{33}+F(\sigma_{22}-\sigma_{33})^2\\ &\quad +G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2=1\end{aligned} \tag{7}$$

The constants A, B, F, G and H are the material coefficients while, x,y and z are normal to the mutually orthogonal planes of symmetry of the material. The criterion does not involve any shear stresses and cannot account for the continuous variation of the plastic properties between the material axes of symmetry [10].

4 Determination of Anisotropic Properties

The deep drawing operation is a plane strain forming operation in which the flow strength is less along the plane of the sheet compared to thickness direction. The flow strength of sheet metal in the thickness direction is difficult to measure, and the plastic strain ratio 'r' can be used to determine strength in thickness direction by the use of Eq. 8. The 'r' is the ratio of width strain to thickness strain.

$$r = \frac{\epsilon_w}{\epsilon_t} \tag{8}$$

where ϵ_w is the true strain in the width direction and ϵ_t is the true strain in the thickness direction. As thickness strain is difficult to measure, the strain ratio r can be determined by using the law of volume constancy. According to the law of volume constancy, ϵ_l $+\epsilon_w$$+\epsilon_t$ $= 0$. Hence the strain ratio also called as Lankford parameter can be rewritten as shown in Eq. 9.

$$r = \frac{\epsilon_w}{\epsilon_w + \epsilon_t} \tag{9}$$

But the strain ratio r is different in different directions on the plane of the sheet. Hence it is necessary to use the average of the strain ratios measured at 0^0, 45^0 and 90^0 to the rolling direction of the sheet to obtain an average strain ratio called as normal anisotropy and is expressed as in equation 10.

$$r = \frac{r_0 + 2r_{45} + r_{90}}{4} \tag{10}$$

where r_0 is the strain ratio in the longitudinal direction, r_{45} is the strain ratio measured at 45^0 to the rolling direction, and r_{90} is the strain ratio in the transverse direction. If flow strength is equal in the plane and thickness directions of the sheet, then r = 1. For r > 1, is the case where the strength of the sheet along normal to plane greater that of average strength of along the plane. When, r > 1, the material resists for uniform thinning and hence the material is of superior in drawing process. In general higher the r value, deeper is cup formed in deep drawing process. Variations of flow strength in the plane of the sheet is termed as planar anisotropy represented by δ r and expressed in equation 11.

$$\delta r = \frac{r_0 - 2r_{45} + r_{90}}{4} \tag{11}$$

where δr is the variation in strain ratio. Planer anisotropy is the cause for ears formation in the cup top and leads to uneven height of the cup that needs to perform do trimming process after drawing operation. A perfectly isotropic material would have r = 1 and δr = 0. These two parameters are convenient measures of plastic anisotropy in sheet metals.

The drawability is also a measure of formability and it can be expressed in terms of a limiting drawing ratio or percentage of reduction based on results of Swift cup testing. The limiting drawing ratio is the ratio of the diameter D of the largest blank that can be successfully drawn to the diameter of the punch d. Mathematically it can expressed as shown in equation 12.

$$LDR = \frac{D}{d} \tag{12}$$

The material used in this study is the aluminum alloy AA6111. Testing specimen were prepared as shown in fig 2 from a rolled sheet of 0.9 mm thickness. The specimens were tested along the three directions at room temperature, with the tensile axis being parallel (0^0), diagonal (45^0), and perpendicular (90^0) to the rolling direction of the material used [11]. The various mechanical properties of sheet metal that were evaluated from tensile testing of sheet metal is as follows.

Table 1. properties of aluminium alloy AA6061

Material Property	Direction	value
Poisson's ratio	—	0.33
Yield strength (Mpa)	Rolling direction	46.70
	45^0 to rolling direction	48.30
	Transverse direction	46.30
Strain hardening exponent n	Rolling direction	0.27
	45^0 to rolling direction	0.29
	Transverse direction	0.293
Anisotropy factor	45^0 to rolling direction	0.388
	Rolling direction	0.935
	Transverse direction	0.640

The process of obtaining forming limit diagram involves three steps. In the first step a circular or square grids are etched on the specimens with 2.5 mm or other convenient sizes. The specimen can be subjected to deformation until necking or fracture appears. Finally, the deformation and then the strains i.e., major and minor strains are evaluated for the grids necked region very near to the fracture. The obtained major and minor strains are plotted on the forming limit diagram. In order to obtain a wide range of forming limit curve the specimen widths are varied and then different strain paths and strain values are obtained.

Among the different methods of determination of anisotropic properties, uniaxial tensile tests, biaxial stretching tests, hydraulic bulge tests, Nakazima tests are important methods that are being effectively used in sheet metal forming applications.

5 Experimental setup

The uniaxial tensile tests were carried out under 500 kN and a normal speed of 5mm/min. The uniaxial tensile tests have been conducted in order to determine yielding strength, ultimate tensile strength, strain hardening exponent, anisotropy factor. The experiments had been conducted according to ASTM-E517 standard [12]. The material used was AA6111 and the specimens were prepared for having different widths of 25 mm, 50 mm, 75 mm, 100 mm, 125 mm 150 mm, 175 mm, 200 mm with thickness of 0.9 mm. Before specimen stretching, circle grids of 5mm diameter are first marked on the surface of the test specimen. Once the specimen tested for stretching, incipient necking takes place before fracture. The deformed circles very near to fracture were measure for determination of the major and minor strain evaluation. A camera was used to capture images of the deformed circles near the fracture.

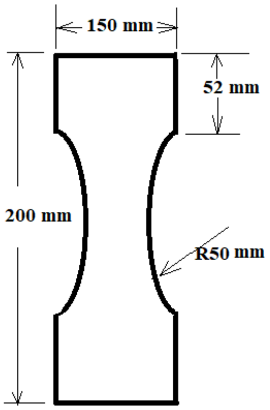

Fig. 2. Test testing sample ([?])

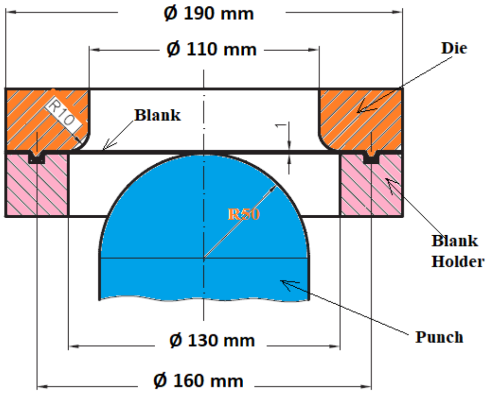

Fig. 3. Principle of the Nakajima test with a hemispherical punch, 100 mm dia

6 Construction of Forming Limit diagram

Formability describes the capability of a sheet metal to undergo plastic deformation in order to get some shape without defects. Forming limit diagram is very useful in die design optimization, die tryout and quality control during production.

In order to measure the FLD, the hemispherical dome stretching process that induces different strain evolution at the central area of the specimen. Each test with different specimen develops different strain path characterized by the ratio of minor vs. major principal surface strain. The different specimens are sufficient to cover the range from uniaxial traction to balanced biaxial traction. These strain ratios cover both the branches of the forming limit diagram as shown in Figure 2.

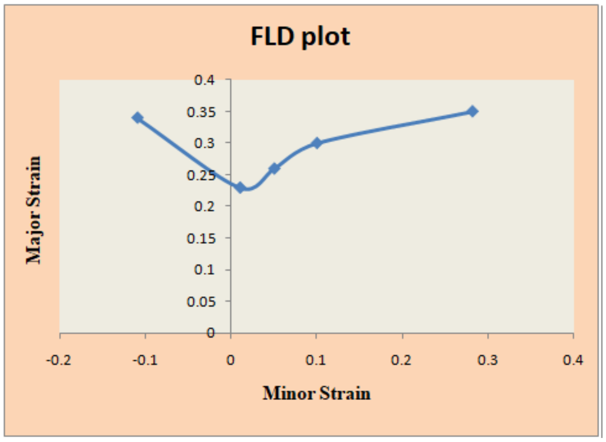

Fig. 4. Forming limit diagram

The data plotted on major and minor strain axes and thus the forming limit diagram were constructed as the boundary curve between safe region (below the curve) and failure region (above the curve).

7 Results and Conclusions

The room temperature mechanical properties were determined by tensile testing, with specimen axis oriented at 0^0, 45^0 and 90^0 to the rolling direction. The conventional parameters such as strain hardening exponent, normal anisotropy, planar anisotropy were evaluated. The forming limit curve for aluminum had been constructed as shown in Figure. FLD is very important formability assessment tool for many sheet metal forming processes such as deep drawing in which by measuring the strain induced can assess the severity of the strains. The FLD also helps in deciding number of drawing operations in multi step deep drawing process.

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