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EXPERIMENTAL ANALYSIS OF FORMING LIMIT DIAGRAM OF AISI 1008 STEEL

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ABSTRACT

The use of sheet metal forming simulations has reduced lead-times and costs for the development of new forming component significantly. The accuracy of the simulations is to a large extent dependent on the quality of the material properties provided as input to the simulations. Improving the quality of the material properties is the key factor in order to further increase the accuracy of the simulations. This study is focused on the forming limit properties of AISI 1008 sheet metal. In this paper among the various well-known analytical and empirical methods, Singh-Rao model, Swift-Hill model and NADDRG model are used for analytical prediction of FLD. The assumptions made in each method are emphasized and their effects on the predicted forming limits are demonstrated. There are many methods for finding the experimental FLD. In the present study experimental work has been performed using Limiting Dome Height test and Erichsen test for finding the FLD. Experimental Set up for Limiting Dome Height test is prepared and find the forming limit is obtained by circle grid analysis method. Standard Erichsen cup test apparatus is used to perform required test. The results obtained during experimental study is reported along with the result obtained using analytical methods.

Keywords: *Forming Limit Diagram, Limit Dome Height Test, Erichsen Test.*

1. Introduction

The sheet metal forming receives more and more application in the domains of automotive and aeronautics. In sheet metal forming operations, the sheet can be deformed only to a certain limit that is usually imposed by the onset of localized necking, which eventually leads to fracture. A well-known method of describing this limit and predicting the occurrence of necking is the forming limit diagrams (FLDs) introduced by Keeler and Backofen in the 1960s (Keeler and Backofen, 1963). In FLDs, a FLC (forming limit curve) represents a plot of major and minor available principal strains in the plane of the deformed sheet corresponding to the occurrence of the necking.

Formability is the ability to impart plausible geometry to the work piece and is the sole criterion from manufacturing perspective. Formability is measured using forming limit diagram (FLD). However, considering the functional aspect of the sheet metal component, the maximum reduction in thickness is specified for each application. The experimental method of FLD generation is by measuring the major and minor strains at the onset of failure. The major and minor strains are measured at certain locations and are compared against the Finite Element Simulation results. The major and minor strains represent only the surface strains captured by the deformation of the grid circles. The thickness strain is calculated based on volume constancy principle from the surface strains. The major strain and minor strain are compared between experimental data and simulation.

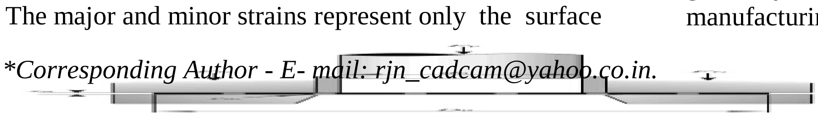

Fig. 1 Schematic Set Up of LDH

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using forming limit diagram (FLD). However, considering the functional aspect of the sheet metal component, the maximum reduction in thickness is specified for each application. The experimental method of FLD generation is by measuring the major and minor strains at the onset of failure. The major and minor strains are measured at certain locations and are compared against the Finite Element Simulation results. The major and minor strains represent only the surface strains captured by the deformation of the grid circles. The thickness strain is calculated based on volume constancy principle from the surface strains. The major strain and minor strain are compared between experimental data and simulation.

1.1 Limit dome height test

Limit Dome Height Test simulates the fracture conditions under plane strain. This test provide the information of allowable height of the dome prior to the facture. Sheet metal strips of varying width are clamped rigidly in blank holder and then stretched over hemispherical punch (The schematic set-up of LDH and operational set-up of LDH are shown in fig. 1 and fig 2 respectively). The height at which the dome fails shows a minimum height at critical blank width. The minimum height is known as the limiting dome height near plane strain (LDH_0). The extend of performance of LDH test can be obtained by Limiting Drawing Ratio (LDR); which can be defined as;

Limiting Drawing Ratio (LDR):

$$LDR = D_o/d_o \tag{1}$$

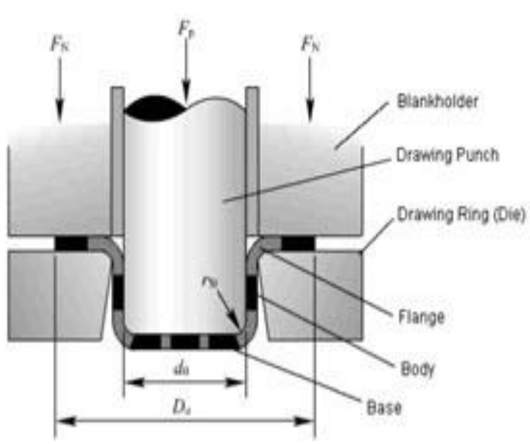

Fig. 2 Operational Set Up of LDH

1.2 Erichsen test

To determine forming limit diagram, Erichsen cupping test is widely used. It estimates the sheet metal formability under stretching conditions. The sheet is clamped between two polished flat plates with hole diameter D and a ball of diameter d is pressed into the sheet metal until failure occurs (The schematic set up of Erichsen test and operational set up of Erichsen shown in fig. 3 and fig. 4. respectively). The height of the cup, h at failure is used as the formability index. The larger the height h the greater is the sheet metals ability to resist necking instability during forming.

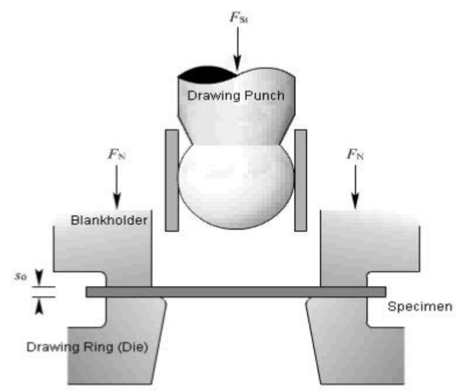

Fig. 3 Schematic Set Up of Erichsen

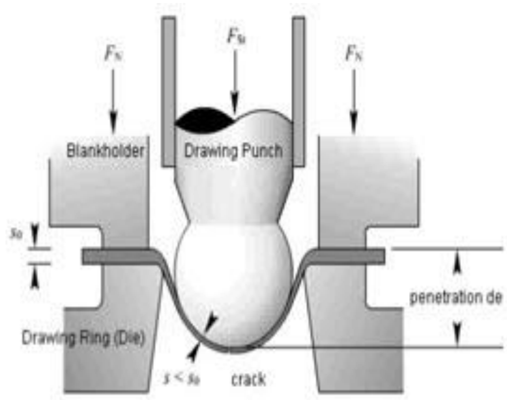

Fig. 4 Operational Set Up of Erichsen

1.3 Circle Grid Method

The surface strain developed during forming can be obtained by experimental strain measurement viz. circle grid marking method. The sheet metal surface is imprinted with circles, which after forming elongates into ellipses. The major and minor axes of the ellipse give the respective strain. Grid marking is the process of printing circles of definite diameter in the area of interest on the sheet metal blank. The strains accompanying the plastic deformation process and hence the FLD can be studied from the deformation of the grid circles. The sheet is marked with the 2.5mm diameter grid before forming process is carried out. After the sheet metal is deformed into desired shape, strain distribution can be visualized and critical areas of strain will be found by FLD (Forming Limit Diagram).

1.3.1 Measurement

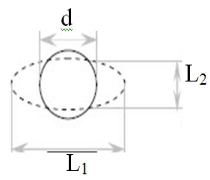

Fig. 5 Deformation of Circle

After deformation the circle is deformed into ellipse as shown in fig. 5. The direction of the strains is indicated by the major and minor axis of the ellipse. After sheet metal is formed the marked circles will deformed into ellipses of different sizes. The major and minor strain of the ellipse can be obtained based on measured values of length along major and minor axis of ellipse.

Major strain $$\varepsilon_1 = \frac{(L_1 - d)}{d} * 100 \quad (2)$$

Minor strain $$\varepsilon_2 = \frac{(L_2 - d)}{d} * 100 \quad (3)$$

2. Hyperform Simulation

In the present work an attempt has been made to perform finite element simulation for prediction of forming limiting diagram. The punch and die set assembly along with the specimen was modelled in Pro-E Wildfire 3.0 and exported as *.IGES in Hyperform finite element sheet metal forming software which is widely used for the simulation experiments for sheet metal forming problems. The Hypeform simulation is done for the case referred in the present study. Necessary input conditions were given viz. Blank material properties (i.e. Yield Strength, Ultimate Strength Strain hardening exponent strength coefficient, R_0, R_{45}, R_{90}), Press Speed, Punch Stroke, Binder force etc. to Hyperform pre-processor. The simulation of the modelled input was done using “LS-DYNA” Solver.

This input file exported to LS-DYNA which solves the problem and generate d3plot file which is a post processing file. Load d3plot file on the load result panel of Hyperform which opens in the Hyperview for viewing the results. The provision is available in Hpyerview to get the various graphical image of different results viz. Forming Limit Curve, Strain distribution etc. Fig. 7 shows the typical forming limit curve as a output of Hyperform simulation. Similarly, deformed blank geometry along with strain distribution can also be seen in fig.8.

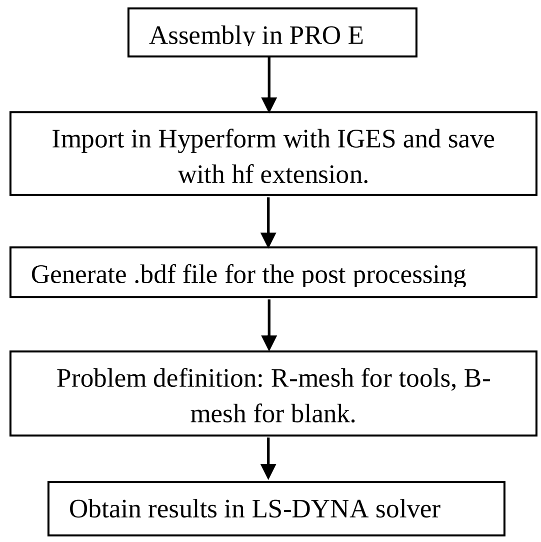

Fig. 6 General Work Flow Diagram

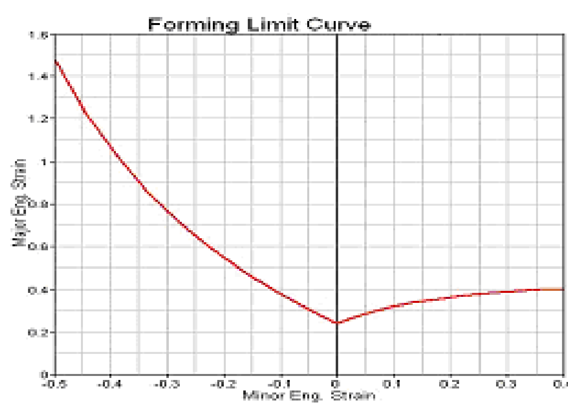

Fig. 7 Forming Limit Curve

Forming limit diagram obtained through the Hyperform simulation is shown in fig.9. In forming limit diagram, points show the major strain and minor strain of the material and lines shows the forming limit of the material. The various stage of the forming can be depicted from this curve based on different colours. In the diagram red colour shows the limiting line indicating failure of the material, above this line the material is failed. If during the operation any point cross this limiting line, it indicate the failure of the sheet. Yellow colour shows the marginal zone for the material, this is a zone between the safe limit of the material and failure limit of the material. Green colour shows the safe zone for the material, in this zone material gets its desired shape during the operation without generating any failure during the operation. Blue colour shows the compression zone of the material, in this zone the failure occurs at the outer edge of the material called the wrinkling failure of the material. The cyan colour zone of the material is a loose material zone means in this area material is not affect due to the load.

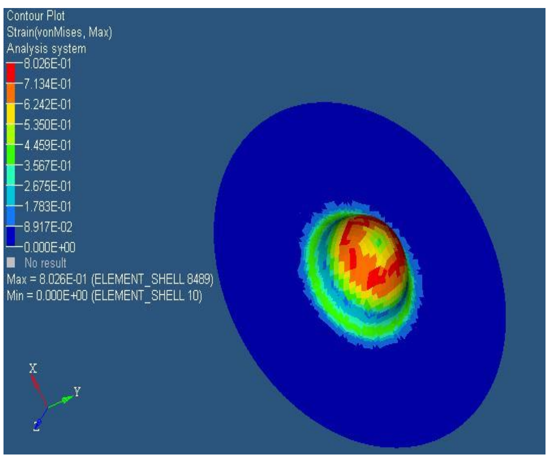

Fig. 8 Strain Distribution

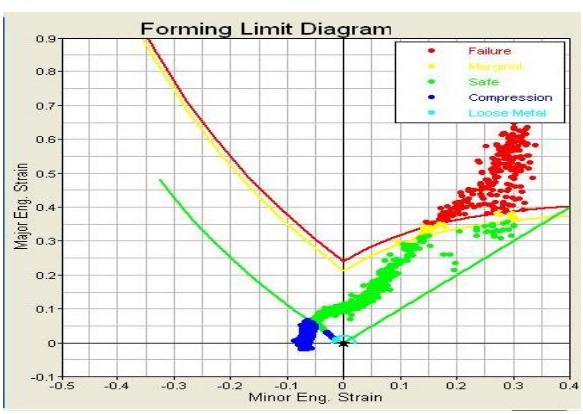

Fig. 9 Forming Limit Diagram

3. Experimental Work

3.1 Procedure for determination of FLD through LDH

Limit Dome Height (LDH) test has been performed under the present study. For performing the LDH test different thickness and diameter combination were selected. Such 24 specimens is cut from the sheet by circle cutting tool as per the dimension of the blank shown in the table 1. To measure the experimental strain, circle grid marking method is used. The circular grid marking is done by laser source on the specimen. These grids marked blanked put on the die of the LDH tool clamped on the press. Material used for making binder, die and punch are mentioned in table 2. For performing the test, press having capacity of 63 tone operated with 45 SPM. After performing the test, specimen removes from the press and put on the tool makers microscope for measure the major axis and minor axis of the elongated grid. Total 10 points measured on the tested specimen in 0°, 45° and 90° direction to the rolling direction of the specimen.

Six different size of specimen are used for performing the test as mentioned in the table 1. The proposed work is to estimate the FLD of AISI 1008 used in the retainers of the bearing, hence the dimension of the blank is selected based on the dimension of the sheet which are widely used in the retainers.

Table 1: Blank Dimension

Blank	Thickness in mm	Diameter in mm
1	1.85	107.0
2	1.55	106.1
3	1.28	105.23
4	1.55	92
5	1.3	82.44
6	1.28	75.44

Table 2: Material Used

Sr.No.	Part Name	Material	Qty.
1	Binder	Mild Steel	1
2	Die	Air hardened tool steel	1
3	Forming Punch	Air hardened tool steel	1
4	Blank	AISI 1008	6

3.2 Results from LDH test

Forming limit diagram obtained after experimental method by LDH test has been compared with the FLD results obtained through various theoretical method and numerical method. The Singh-Rao model, Swift-Hill model and NADDRG models are used to predict the forming limit diagram.

3.2.1 Swift-Hill model

The theoretical analysis is based on the plastic theory of Hill taking orthotropic anisotropy into account, the equivalent stress increment σ_i defined as follows:

$$\sigma_i = (\sqrt{3(1+r)} / \sqrt{2(2+r)})\sqrt{\sigma_1^2 + \sigma_2^2 - (2r/(1+r))\,\sigma_1\sigma_2} \quad (4)$$

It has been proven that a good simulation of the forming limit strains can be given on the basis of the swift diffuse instability theory and the Hill localized instability theory and here swift's and hill's theories are used to calculate the forming limit strains on the left and the right side, respectively, of the FLD.

Assuming that the stress–strain relationship of sheets can be expressed by Hollomon's equation:

$$\sigma i = K\varepsilon in \quad (5)$$

According to Swift's and Hill's criterion combined with above equations, the formulae calculating the forming-limit strains can be written as follows, with α (stress ratio) = σ_2 / σ_1

The Major strain and Minor strain are obtained in this method by two condition viz. (i) ε_2 (minor strain) < 0 and (ii) ε_2 (minor strain) > 0. These two methods are described below.

For $\varepsilon_2 < 0$:-

$$\varepsilon_1 = ((1 + (1 - \alpha) r_m) / (1 + \alpha))n \quad (6)$$

$$\varepsilon_2 = ((\alpha + (1 - \alpha) r_m) / (1 + \alpha))n \quad (7)$$

For $\varepsilon_2 > 0$:-

$$\varepsilon 1 = \frac{[1+(1-\alpha)r_m][1-\frac{2r_m}{1+r}\alpha+\alpha^2]}{(1+\alpha)(1+r_m)[1-\frac{1+4r_m+2r_m^2}{(1+r)^2}\alpha+\alpha^2]}n \quad (8)$$

$$\varepsilon 2 = \frac{[(1+r_m)\alpha-r_m][1-\frac{2r_m}{1+r}\alpha+\alpha^2]}{(1+\alpha)(1+r_m)[1-\frac{1+4r_m+2r_m^2}{(1+r)^2}\alpha+\alpha^2]}n \quad (9)$$

3.2.2 Singh-Rao model

According to the original Sing-Rao proposition, the FLCs can be obtained using the linear regression technique based on the results of calculation using below mentioned scheme taking into account mean plastic anisotropy ratio. On the base of flow rule the surface limit strains for different stress (or strain) ratio can be calculated as:

$$\varepsilon_1 = [\{(1 + 2r_m) \times (\sigma_1 - \sigma_2)\} + (\sigma_1 + \sigma_2)] \times \lambda \quad (10)$$

$$\varepsilon_2 = [\{-(1 + 2r_m) \times (\sigma_1 - \sigma_2)\} + (\sigma_1 + \sigma_2)] \times \lambda \quad (11)$$

$$\lambda = \varepsilon_e / 2(1+r_m)\sigma_e \quad (12)$$

3.2.3 NADDRG Model:

For simplifying the experimental and theoretical determination of the FLD and utilizing the FLD more easily in the workshop, the North American Deep Drawing Research Group (NADDRG) have introduced an empirical equation for predicting the FLD in practise[8]. According to this model, the FLD is composed of two lines through the point ε10 in the plane-strain state. The slopes of the lines located on the left and right side of FLD are about 45° and 20° respectivelty. The equation for calculation of forming limit strain ε10 in term of engineering strain can be expressed as equation 13 when thickness of the sheet is less then the 3.18mm.

$$\varepsilon_{10} :- [\{ 23.3 + (14.13 \times t_0) \times n\} / (0.21)] \quad (13)$$

The comparison of the results obtained through various methods are shown in fig. 10 to fig. 15.

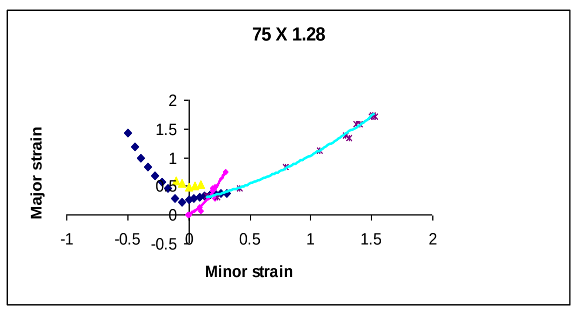

Fig. 10 FLD Prediction for Diameter 75 mm x 1.28mm Thickness

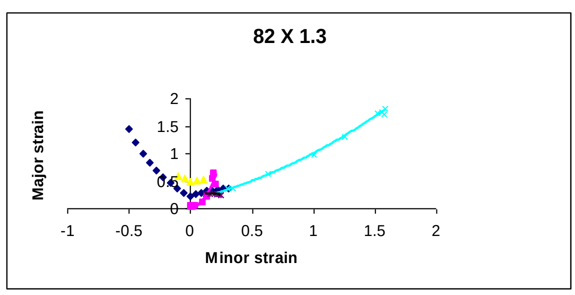

Fig. 11 FLD Prediction for Diameter 82mm x 1.3mm Thickness

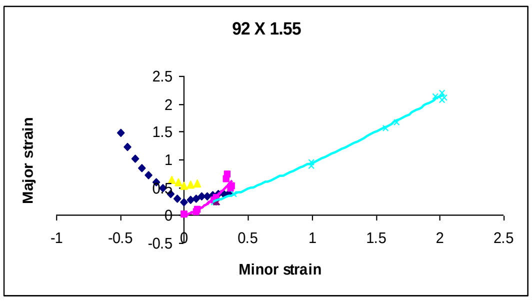

Fig. 12 FLD Prediction for Diameter 92mm x 1.55mm Thickness

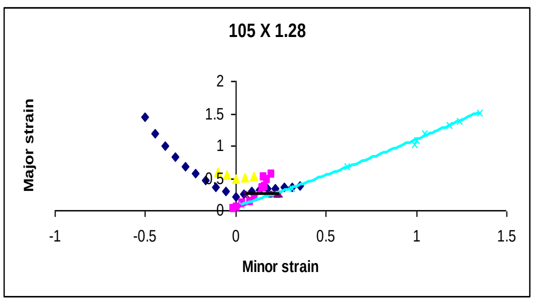

Fig. 13 FLD Prediction for Diameter 105mm x 1.28mm Thickness

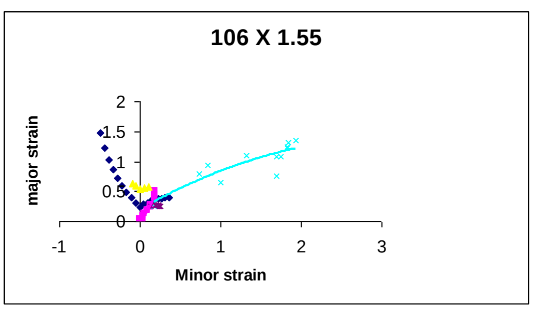

Fig.14 FLD Prediction for Diameter 106mm x 1.55mm Thickness

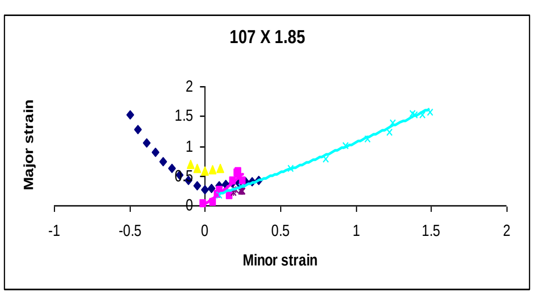

Fig.15 FLD Prediction for Diameter 107mm x 1.85mm Thickness

3.3 Procedure for determination of FLD through Erichsen

The Erichsen cupping test also has been performed in present study. Similar, blank dimensions are used as reported in table 1. The circle grid has been marked using laser prior to the test to obtain strain after the test.

The grid marked blank is held between the die and binder of Erichsen testing machine and sheet was deformed by pressing the punch manually. Punch penetrates in to the blank by manual load of the hand wheel. As the punch moves towards the blank, blank is stretched and circular grid takes the elongated shape. Test has been performed till the crack initiated on the blank, which is confirmed by the mirror and lamp attached on the Erichsen testing machine. The stretch blank then tested for the strain as explain earlier.

Table 3: Specification of Erichsen Testing Machine

Technical Data	Unit	Range
Width of sample	mm	70-90
Thickness of sample	mm	0.1-2
Least count	mm	0.01
Overall dimensions	mm	450 x 500 x 500
Net weight	Kg	20

3.4 Results from Erichsen test

Specimen after performing the Erichsen test is shown in fig.16. Forming limit diagram predicted by experimental method by Erichsen test, theoretical method and numerical analysis are shown in fig. 17 to fig. 21.

Experimental FLD for Limit Dome Height as well as Erichsen test shown in Fig. 22.. This is the same experimental condition as explained in the section 3.1 and section 3.3. After studying the graphs plotted based on the experimental results of for different blank diameter and blank thickness by Erichsen as well as Limiting Dome height Test, Forming limiting diagram generated by both methods are closed to each other with reference to the exponential generated curve based on the experimental data. But, the data obtained from Erichsen test, data are more scattered to each other then the data obtained from Limiting Dome Height test in other words result getting after limiting dome height test is more reliable then the result getting after the Erichsen test.

Fig. 16 Specimen after Erichsen Test

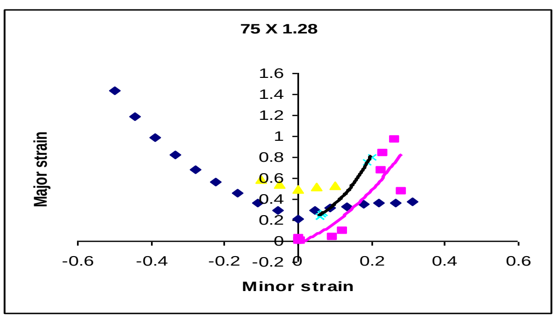

Fig. 17 FLD Prediction for Diameter 75mm x 1.28mm Thickness

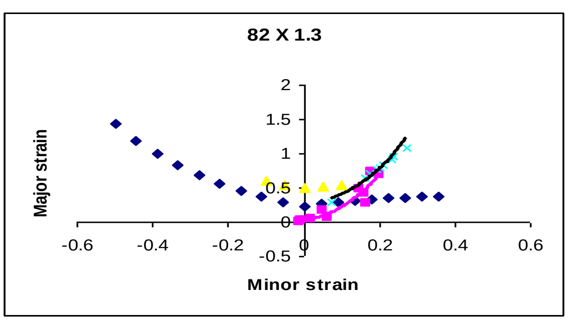

Fig. 18 FLD Prediction for Diameter 82mm x 1.3mm Thickness

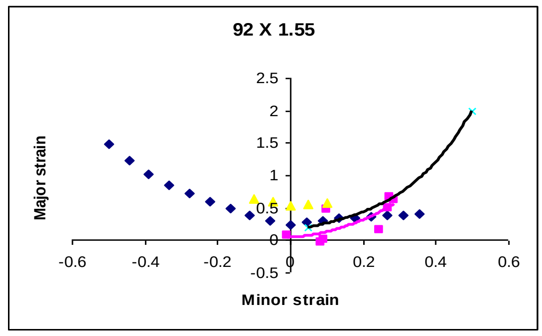

Fig. 19 FLD Prediction for Diameter 92mm x 1.55mm Thickness

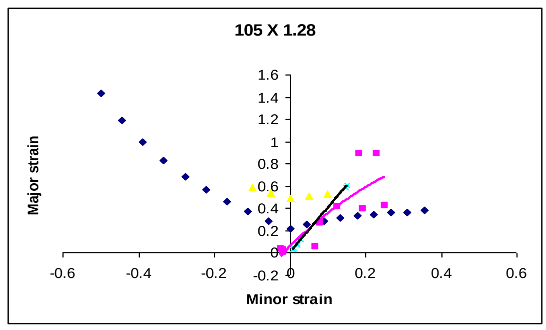

Fig. 20 FLD Prediction for Diameter 105mm x 1.28mm Thickness

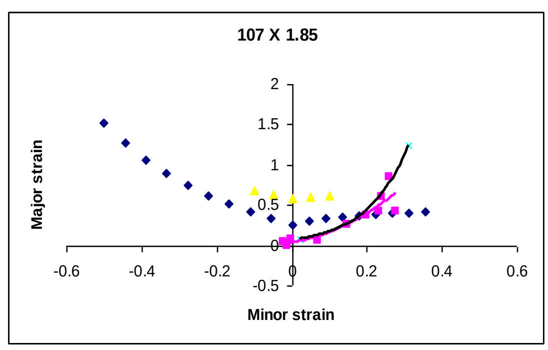

Fig. 21 FLD Prediction for Diameter 107mm x 1.85mm Thickness

4. Conclusions

From the present results the following conclusions could be drawn.

i. Formability test for AISI 1008 steel sheet is performed. Forming limit is characterized by the appearance of localised necking on the sheet surface. FLD is measured by identifying the safe and necking regions.

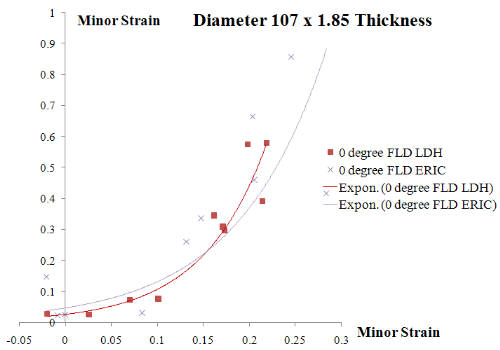

Fig. 22 Experimental FLD for LDH and Erichsen Method

ii. Theoretical prediction of FLD based on the generalised localized necking criterion is validated with test data of AISI 1008 steel sheets.

iii. With increasing sheet thickness by 17%, the FLD goes down by the 10.15%.

iv. The Hyperform results show FLC at higher level than the experimental results and lower than NADDRG model. This shows NADDRG model can be used initially to begin with design of new forming component.

v. The tool used for numerical prediction is Hyperform –LSDYNA combination. The numerically predicted results are compared with experimental results.

vi. Forming limiting diagram generated by Erichsen as well as Limit Dome Height test are closed to each other with reference to the exponentially generated curve based on the experimental data.

vii. Data obtained from the Erichsen test are more scattered then the limit dome height test and hence LDH test results may used for FLD.

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Nomenclature

Symbol	Meaning	Unit
D_o	Blank Diameter	mm
d_o	Punch Diameter	mm
F_P	Punch Force	N
F_N	Binder Force	N
r_m	Draw radius of die	mm
r_n	Punch radius	mm
s_o	Initial thickness of blank	mm
s	Final thickness of blank	mm
d	Grid diameter	mm
L_1	Major axis dimension of grid after trial	mm
L_2	Minor axis dimension of grid after trial	mm
R_0	Material anisotropty in parallel to rolling direction	
R_{45}	Material anisotropy in 45 ° of rolling direction	
R_{90}	Material anisotropy in transverse direction to rolling direction	
r	Planar anisotropy	
K	Material strength co-efficient	N/mm^2
σ_1	Principle stress in X direction	N/mm^2
σ_2	Principle stress in Y direction	N/mm^2
t_o	Initial thickness of specimen	mm

