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Determination of Measurement Uncertainty in Extracting of Forming Limit Diagrams

M. Mahboubkhah, H. Fayazfar

Abstract**—**In this research, Forming Limit Diagrams for super-tension sheet metals which are using in automobile industry have been obtained. The exerted strains to sheet metals have been measured with four different methods and the errors of each method have also been represented. These methods have been compared with together and the most efficient and economic way of extracting of the exerted strains to sheet metals has been introduced. In this paper total error and uncertainty of FLD extraction procedures have been derived. Determination of the measurement uncertainty in extracting of FLD has a great importance in design and analysis of the sheet metal forming process.

Keywords**—**Forming Limit Diagram, Major and Minor Strain, Measurement Uncertainty.

I. Introduction

DESPITE the automation that has been implemented in the various techniques for manufacturing sheet metal parts, die and part in the majority of cases is still an advanced art. The variables that enter in to the forming of sheet metal parts are numerous and their interactions are extremely complex. All of these factors (Material flow properties and ductility, die geometry and material, lubrication, press speed, blank holder pressure, etc) contribute to the success or failure of sheet metal forming process [1].

Calculation of the stress and strain contribution on the sheet metal surface by analytical or numerical methods and comparison of their results with permissible quantities lead to get away from the necking problems. The Forming Limit Diagram (FLD) represents the acceptable limits of strain in a curve with two principle surface strains. Any combination of the two surface strains and falling below the FLD curves is considered acceptable and any combination falling above it will produce failure. Failure is defined as the appearance of localized thinning or necking in sheet metals. The using of the FLD concept in predicting failures in sheet forming operations was pioneered by Keeler but in subsequent work Keeler and Goodwin used production stampings to establish the FLD for low-carbon steels, which has been called Keeler-Goodwin curve. Since the FLD represents the first local plastic instability [2-5]. Thus precise construction of the FLD curve has a key importance in sheet metal forming techniques. Various methods have been proposed for measuring of the major and minor strains of sheet metal surface [6]. In this paper for measurement of the deformed circle diameters, four different methods have been employed and the error and uncertainty of measurements have been compared with together.

M.Mahboubkhah is with Manufacturing Engineering Group, Mechanical Engineering Department, Tabriz University, Tabriz, Iran (corresponding author to provide phone: +984113392485; fax: +984113356026; e-mail: mahboobkhah@tabrizu.ac.ir).

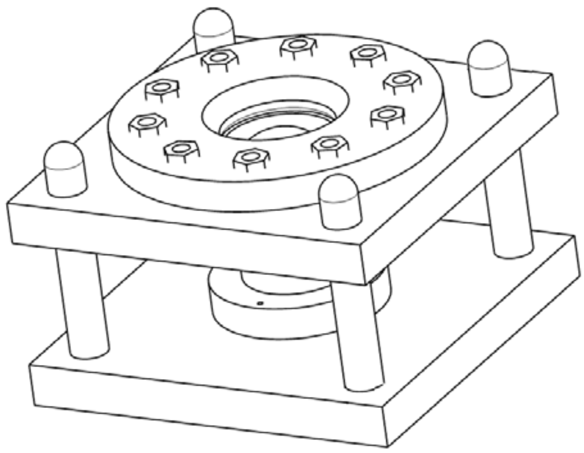
H. Fayazfar is with Metallurgy Department Sharif University of Technology, Tehran, Iran (e-mail: fayazfar@gmail.com).

II. Preparation of the Die and Sheet Metal Specimens for Implementation of Deep Drawing Test

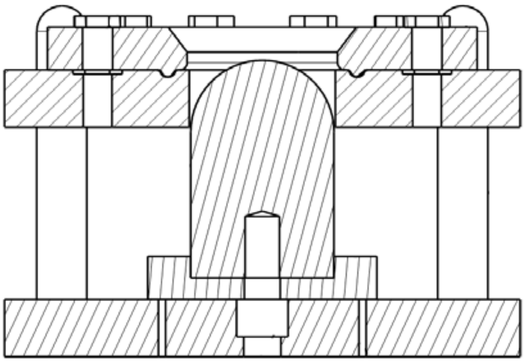
To obtain the limits of major and minor strains, deep drawing test, by means of a hemispherical punch has been done. The punch-stretch apparatus and sheet metal specimens have been prepared according to ASTM standard [7].

A. The Punch-Stretch Apparatus Preparation

According to ASTM standard the hemispherical punch radius amounts to 50 mm. A single stroke press is applied for deep drawing test. Another additional stroke for stripping the formed sheet metal is provided by means of four standard springs according to Fig. 1. The hemisphere bead on the upper part of the die is used to reduce required blank holder force.



(a) 3D drawing of deep drawing die



(b) Vertical section of stretching die

Fig. 1 Drawing of stretching die

B. The Preparation of Sheet Metal Specimens

To construction of the FLD curve at least four sheet metal specimens with 200 mm length and various widths are required. However by increasing the sheet metal specimens the accuracy of FLD curve is increased. In this research three types of steel sheets (St12, St13 and St14) have been used. For each type, 14 specimens with 180mm length, 7mm thickness and various widths (17.5, 30, 42.5, 55, 67.5, 80, 92.5, 105, 117.5, 130, 142.5, 155, 167.5 and 180mm) were prepared. The circle marks on the specimen blank have been etched electrochemically. The ratio of punch diameter to circle diameter is equal to 40, consequently the circle diameter amounts to 2.5mm. A typical etched and marked sheet metal has been illustrated in Fig. 2.

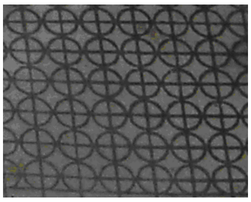


Fig. 2 A typical etched sheet metal with 2.5mm circle diameter

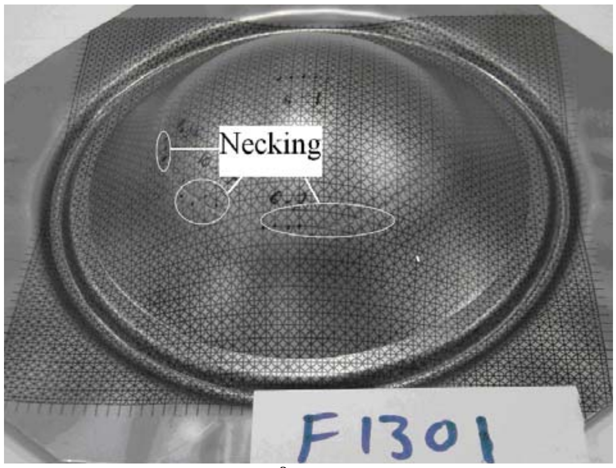
C. Implementation of Deep Drawing Test

For implementation of test, sheet should be fixed by die plate. Tightening ten M20 bolts (with 25 ft-lb) on the blank holder plate (with 305mm diameter) will produce 178 KN force.

Stretching of the sheet metal is starting when the press ram is moved down. The punch-displacement rate is kept constant at 0.42 mm/s. It is preferable to deform the specimen to the point of necking. This is practical by stopping the press ram movement. When the force in the force-displacement curve starts to drop, the maximum amount of the punch movement will be equal to hemispherical punch radius. Schematic set up of the die under hydraulic press is illustrated in Fig. 3.

Fig. 3 Schematic set up of the die under hydraulic press

At last the press ram is moved up and accordingly the deformed sheet metal can be separated from punch. The samples of deformed sheets with necking effects have been illustrated in Fig. 4.



(a) 180×180 mm^2 sheet metal specimen

(b) 30×180 mm^2 sheet metal specimen

Fig. 4 Two samples of deformed sheets with necking effect

After the forming process, in order to access to the major and minor strains of the necking zones, the maximum and minimum diameters of ellipses (deformed circles) should be measured. Various measuring methods have been considered in this part.

III. Measurement the Major and Minor Strains of Sheet Metal

The proper selection of measuring method is one of the most important and cost effective parts of the FLD curve construction. The major and minor strains (e_1, e_2) with an initial length ($l_\circ$) of 2.5 mm can be calculated as following:

$$e = \left(l - l_\circ\right)/l_\circ \qquad (1)$$

Where $l_\circ$ is the maximum or minimum deformed length of the circle diameter.

In this research for measuring diameters of ellipses four different methods has been employed. Then the maximum repeatability and accuracy of each method has been considered.

- In the first method a caliper with 0.01 mm resolution has been used for measuring the ellipses diameters. The operator error due to misaligning the caliper edges with circle lines makes 0.1 mm uncertainty for this measurement.
- In the second method, the circle diameters of 2D image of sheet metals have been measured by means of computer software. The maximum uncertainty of this method is 0.15 mm due to converting the 3D image to 2D image and furthermore the alignment errors.
- In the third method, the form measuring instrument (Form Talysurf) and a 10 times magnification lens have been employed to measure the circle diameters (Fig. 5). The accuracy of Form Talysurf instrument is 0.001mm, but the total uncertainty of measurement is 0.01mm.

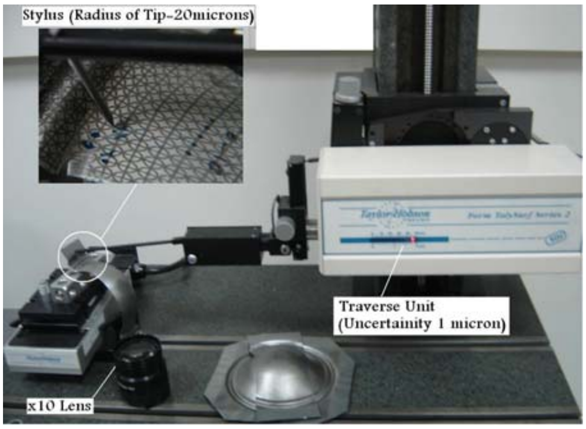
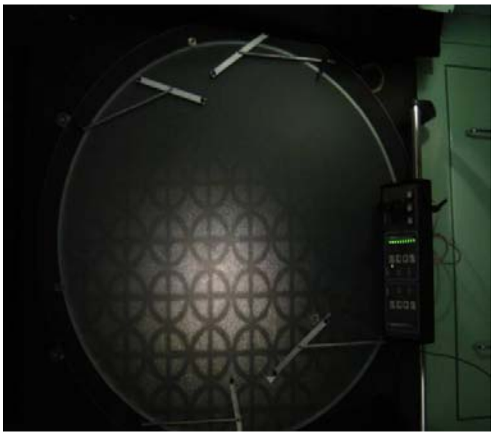


Fig. 5 Measurement of circle diameters by Form Talysurf

- In the forth method the topography capability (Episcopic) of Profile Projector instrument has been used for measurement (Fig. 6). The resolution of CNC table of Profile Projector is 0.001 mm. The surface of specimens should be perpendicular to the instrument light beam in measuring process. The repeatability and maximum uncertainty of this method amounts to 0.03 mm.

(a) Test set up for Profile Projector



(b) Profile Projector screen with diameter of 1m

Fig. 6 Measurement of circle diameters by Profile Projector

IV. Drawing the Forming Limit Diagrams from Extracted Data Tests

After measurement of the maximum and minimum diameters of deformed circles in necking and failed zones of the sheet metals, the major and minor strains (e_1, e_2) of the sheet surfaces can be calculated from Eq.1.

A sample of the FLD curve of sheet metal (St13) has been illustrated in Fig. 7. By using the safe, necking and failed points in the diagram, the proper curve fitting can be drawn.

According to Fig. 7 the distribution of the necking points around FLD curve amounts to 7% approximately. In the other words the boundary of the safe and failed strains in FLD curve has been constructed with 7% error.

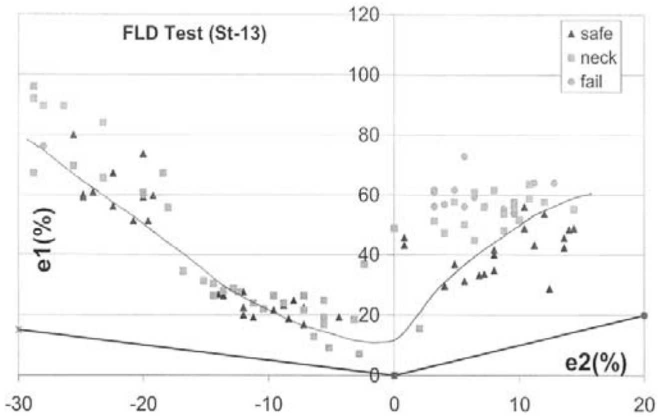


Fig. 7 Forming Limit Diagram of the sheet metal (St13)

V. Conclusion

In this paper the construction process of the Forming Limit Diagram for some sheet metals (St12, St13 and St14) have been investigated. Also a novel approach for calculation of the measurement error and uncertainty of strains of the sheet metals has been proposed. These considerations have a key importance in sheet metal forming design and analysis. Major and minor strains of the sheet metals have been measured by various methods and the error and uncertainty of each method have been derived.

As a result the error of measurement by means of the digital caliper is equal to 4% (Error in diameter measurement; 0.1mm/2.5mm; initial diameter length). Where the measurement of 2D image of deformed circles was produced 6% error (0.15mm/2.5mm). The Profile Projector instrument has also been produced 1.2% error (0.03mm/2.5mm). In two first methods the errors are 4% and 6% respectively, thus these methods are not recommended due to large errors. Regardless of the high measurement accuracy of the Form Talysurf instrument in comparison with Profile Projector, measurement with Form Talysurf is not recommended, because it takes more time and it is a hard work.

Furthermore 1.2% measurement error of the Profile Projector instrument is acceptable in comparison with 7% constructed error of the FLD curve fitting (Fig. 7). With respecting to these results, the FLD measurement uncertainty produced by Profile Projector, amounts to 7.6%.

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