Construction of FLD using CGA

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Abstract. Sheet metal deforms plastically into a desired shape and it depends upon the formability of sheet metal. Different strain values just before the localized failure can be described through principal strains shown in forming limit diagram (FLD). Shop floor problems in forming auto body door panels etc. can be investigated successfully using circle grid analysis (CGA). CGA is one of the important strain assessment methods for sheet metal formability through the construction of an FLD diagram. The circular grid pattern is etched over the surface of the blank and circles are deformed into ellipses during the forming operation. The circles at different places test the different circles' deformation zone will be deformed into different size ellipses based on the forming severity. The grid circle method is one of the important strain measurement systems generally used in the sheet metal stamping process. This method provides clear knowledge of the formability of sheet metals and is only used as a research tool because of the slowness and tediousness involved in getting the results from each deformed circle. But in recent years, there is a considerable improvement in this method due to the advanced application of computers along with a solid-state camera is able to give fast and accurate results.

Keywords: FLD diagram · Circle grid method · Mylar tape · split-ring test.

1 Introduction

Sheet metal forming is an important manufacturing process where the metal sheet deforms plastically into a desired shape. The quality of the formed component highly depends upon the formability of sheet metal. The formability of sheet metal is a tendency of undergoing deformation without fracture or wrinkling. The combination of different strain values just before the localized failure is described in terms of the principal strains plotted in a 2D diagram known as forming limit diagram (FLD). The FLD is a plot of limit strain on the coordinates of major strain and minor strain. The most commonly used failure criterion for sheet metal forming applications is still FLC despite its all drawbacks. This is due to its simplicity, excellent performance, and for its historical reasons in many cases.

Different shop floor problems of sheet metal forming of auto body door panels etc., can be investigated successfully using circle grid analysis (CGA). CGA is one of the important strain assessment methods for sheet metal formability through the construction of FLD diagram [5, 4, 7]. The circular grid pattern is etched over the surface of the blank and circles are deformed into ellipses during the forming operation. The circles at different places test the different circles' deformation zone will be deformed into different size ellipses based on the forming severity. The grid circle method is one of the important strain measurement systems generally used in the sheet metal stamping process. This method provides clear knowledge of the formability of sheet metals and is only used as a research tool because of the slowness and tediousness involved in getting the results from each deformed circle. But in recent years, there is a considerable improvement in this method due to the advanced application of computers along with a solid-state camera is able to give fast and accurate results.

The development of the FLD began with tests performed by Keeler and Backofen on the stretching of circular blanks by a hemispherical punch. Keeler subsequently proposed the use of electrochemically etched grids to measure strain histories and strain distributions as a tool for determining forming limits. Goodwin used a combination of cup and tension tests to obtain a failure band in both the negative and positive quadrants of minor strain, creating the general form of the forming limit diagram.

Aluminum alloys are extensively used in the automotive industry due to environmental norms about decreasing the CO_2 release into the atmosphere. FEA Finite Element Analysis and/or CGA can predict the performance of a forming process when provided with tool geometry, material properties, and kinematics of the process. Considerable effort is putting at present days for modeling of sheet metal forming using several finite element methods and different software is giving different results. It is essential to verify the results with experimental results and this verification needs the measurement of surface strain in the deformed sheet. The FLD can be constructed with measured surface strains[9, 8].

More importantly, its relation with FLD makes it important to do a shape analysis of the chosen yield criterion. Keeping these things in mind, Hill's 1948 anisotropic yield criterion was chosen for study. The concept of the forming-limit diagram introduced by Keeler is now widely used as one of the criteria for optimizing stamping processes and in the designing of dies. Forming limit diagrams can be regarded as material property curves and industrially the curve for a particular material is always established experimentally. Local thinning, splits, tears, and wrinkles cannot be accepted when forming automotive panels. Forming limit diagrams (FLDs) have been determined experimentally by conducting punch-stretching experiments for aluminum-killed extra-deep drawing (EDD) low-carbon steel sheets. The effect of n and r on the strain distribution characteristics has been analyzed. The earing tendency during drawing is expected to be high due to its high planar anisotropy. Sheet metal forming is a widely utilized manufacturing process in the automotive, aeronautical, and consumer goods industries. The manufacturers of automobiles prefer steel for favorable mechanical properties such as high strength, ductility, and toughness.

It is also demanded for vehicle safety and crashing strength of the vehicle Forming Limit Diagrams were evaluated for the Interstitial Free (IF) steels and the tensile properties and formability parameters were correlated with the FLD. The formability of extra-deep drawing (EDD) low-carbon steel sheets have been determined experimentally by conducting punch-stretching experiments.

Different sheet formability assessment tests are available and the Erichsen cup test is most widely used nowadays. The forming limits can be obtained by means of the stretching test with strips and a hemispherical punch. The improved method of this test is to use circle-shaped strips with material removed along arc contours on two opposite sides. Circle grids are imprinted on the blank and the strip undergoes stretching up to fracture. the major and minor diameters of deformed circles are measured and strains are calculated. This data has been used to construct FLD. Traditionally, the deformed grids are measured manually with the aid of transparent tape and a magnifier. Because the grids are so small and the principal direction cannot be recognized accurately, it is tedious and inaccurate to construct FLD by the conventional method. Optical-strain-measurement system was developed to get principal strains from the deformed circles automatically with an image-processing technique. The dimension of the deformed grid is obtained by computing the mean dimension of the inner and outer edges. The solid circle analysis and square grid, a two-view method for three-dimensional deformed surfaces and sheet metal. Formability in sheet metal forming sets limits on the amount of deformation that can be imparted to sheet metal blanks without failure by wrinkling, necking, or fracture. Marciniak (1984) pioneered an integrated vision for the assessment of formability in sheet metal forming by plotting three different types of limits in the principal strain space (Fig. 1a): (i) a formability limit by wrinkling in the lower left-hand part of the second quadrant that takes place when the in-plane stresses acting in a thin sheet are compressive and that is commonly associated to regions of the sheet metal blanks that are unsupported or in contact with only one tool, (ii) a formability limit by necking characterized by a 'V-shaped' curve (designated as the 'forming limit curve' – FLC) that indicates the amount of deformation where aesthetics problems and incipient fracture derived from localized zones of thinning are likely to develop in sheet metal parts and (iii) a formability limit by fracture consisting of two curves (designated as the 'fracture locus') that intersect at the upper right-hand part of the second quadrant and delimit the strain loading conditions where cracks are triggered.

2 Literature survey

Buchar (1996) used circular grid analysis on a car body panel to compare formability of blanks for two different orientations to rolling direction. As discussed by Banabic et al. (2001), the diameter of the grid circles influences the measurement of strain. The important part of the process is imprinting grid 300 circles on the metal surface. Formability of a material is defined as the ease with which a material can be plastically deformed to the required shape and the ductile materials are more suited for forming processes. Fahrettin et al. [10] studied this study, grid marking and measurement methods were discussed in detail and evaluated in terms of measurement accuracy. Abu-Farha et al.[1] performed formability of magnesium AZ31B sheets under hot forming and friction-independent FLCs were constructed clearly distinguishing the zones of safe, marginal, and unsafe forming. Toros. [3] used Marciniak and Kuczynski's theory for investigation in predicting the forming limit strains through the construction of FLD for Al-Cu two-layer metallic sheets. The numerical results for the FLDs were verified by comparing them with the experimental results. The results found were in good agreement with experimental investigations. Marques et al. [6] were investigated through circle grid analysis to support the forming limits found in polymers through rapid photo typing.

3 Circle Grid Method

Grid marking is the process of printing circles of definite diameter in the area of interest in 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 [2]. Carasusan and Fernand (2003) discuss different methods for engraving the grid circles in the blank. Some of the methods are screen-printing, electrochemical method, photo-emulsion method, and Laser etching method. Screen-printing method is one of the easy and cost-effective methods for grid marking. In this method, a framed screen with a semi-permeable membrane (refer to Fig. 5) is made from nylon or other synthetic materials. The screen is placed over the cleaned surface of the blank. Ink is poured on one side of the screen and wiped throughout (refer to Fig. 6) the useful area using a rubber squeegee. On the removal of the screen, grid circles are printed on the blank. Screen-printing method is used in this work considering the ease of availability of resources in terms of materials, labor, and expertise. The accuracy of the process is related to the accuracy of the screen made. Drying of paint during the printing process may clog the semipermeable pores. Frequent washing of the screen is required to avoid the clogging of pores. The selection of ink is important as the ink should not be wiped off during forming. In this case, black paint is used for screen printing.

4 Strain measurement procedure

The surface of the sheet has electrochemically etched with a grid of circles of 2.5 mm initial diameter. The strain loading paths were constructed from the meridional and circumferential in-plane strains (ϵ_1, ϵ_2) at the grid circles as follows:

$$\epsilon_1 = ln(b/d) \quad \epsilon_2 = ln(a/d) \tag{1}$$

where a and b are the lengths of the major and minor axes of the ellipses from plastic deformation of the original grid of circles with an initial diameter d. The

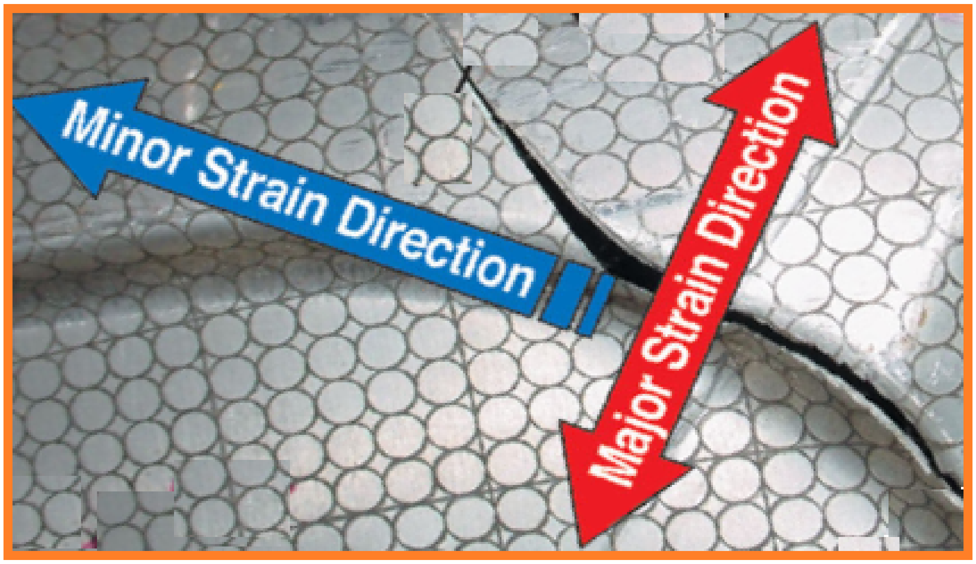


Fig. 1. Major and minor strain direction during the crack

maximum strain pairs at the onset of necking and at very near to fracture are obtained by means of a mathematical procedure that interpolates the experimental strains retrieved from adjacent deformed circles along a direction perpendicular to the crack by a parabolic 'bell-shaped curve' as shown in Fig. 3.

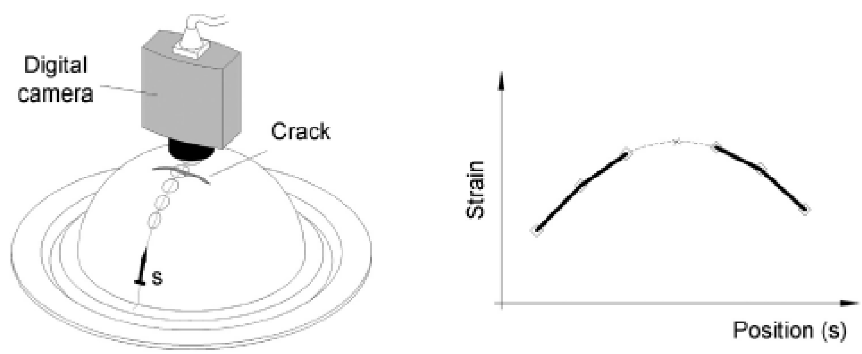
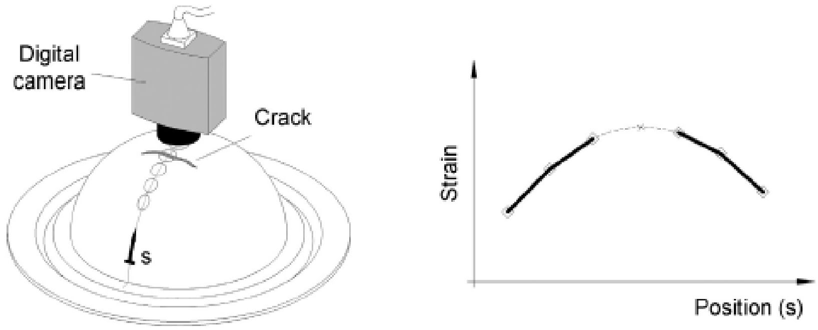


Fig. 2. Schematic procedure to determine the in-plane strains and the onset of necking [**soeiro2015revisiting**]



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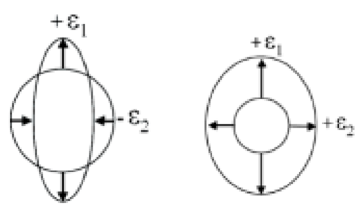

Fig. 4. Ellipse formed after deformation

5 Mylar Tape

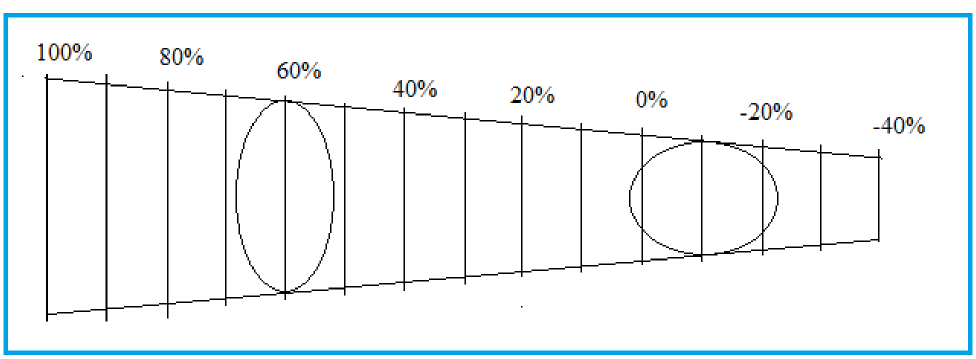

Fig. 5. Mylar tape

6 The Sequence of Activities in FLD construction using CGA Technique

1. Select the blank material to be tested for formability
2. Cut the sheet material into suitable size blanks.
3. Clean the blanks with a soft cloth.
4. Draw the circles of constant diameter (4 mm) with the circular array.
5. Set the die of the required component.
6. Select the punch force and the stroke required for drawing component.
7. Draw the circular blank with the help of the drawing machine.
8. See whether the circular marking is neat and visible.
9. Measure the changed dimensions i.e. Major dia. and Minor dia. of each circle after drawing. 10. Calculate the true strains i.e. Major strains and Minor strains of each reading of the measurement.
10. Tabulate all the data as per the result table. The r shown in Table 2.
11. Plot the forming limit diagram from the strains calculated.

7 Split-ring test

The distribution of residual stresses in the cup can be assessed even with a split test ring. The split-ring test consists of obtaining a ring by cutting from the wall of the drawn cylindrical cup and splitting the ring. The split distance of the split ring will be measured to assess the spring back. This spring back measure can also be used to estimate the circumferential residual stresses in the ring.

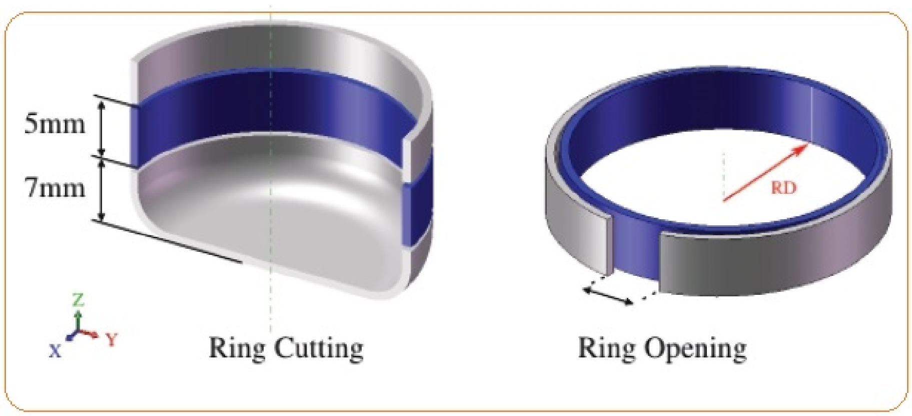

Fig. 6. Split test ring

Rings are cut from the sidewall of a formed cylindrical cup and split perpendicularly to the circle plane, in the rolling direction (RD). Ring gap measurements are performed along the straight line connecting the two ends of the split rings in order to characterize the residual stress state and to measure the spring back effect.

8 Results and Discussions

Various strain measurement methods such as CGM using Mylar tape, split test ring method, etc, have been described in this article. The FLD construction procedure is also described in detail in this article.

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