Obtaining Formability Characteristics Of Automotive Materials Using On-line Strain Imaging System

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Abstract. The formability of automobile sheet material AA6111-T4 was investigated in the hemispherical punch test. Specimens with various geometry and lubrication conditions were utilized to obtain a continuous strain map from a biaxial stretching. The data was processed to obtain strain path and limit strain values as measures of formability. The Strain imaging system, ARAMIS, in which a speckle pattern is utilized instead of the conventional grid system, was employed to capture the strains during the forming process. Features of the evolving dome surface, such as development of shear bands and strain localization were accurately captured and studied. Specimen profile with non-symmetric notches for shearing test in biaxial loading was designed and investigated in both the experimental and the FE approach. The on-line strain imaging method offers a useful approach towards developing an understanding of flow localization, formability and fracture under biaxial loading conditions.

INTRODUCTION

The prediction of the forming limit diagram (FLD) has been widely utilized in the metal forming industry to identify the limit strains of deformed sheets or to evaluate the formability of different metals [1, 2]. Many attempts have been made to obtain the FLDs theoretically and experimentally, such as the theory of localized necking [3], diffuse necking for biaxial loading [4], and the Marciniak-Kuczynski model with initial thickness imperfection [5, 6]. It has been found that FLD is affected by many factors such as r-value, material imperfection, yield criteria, grain size, etc [7-9]. This complexity has made the existing approaches of predicting FLD often unsatisfactory. Theoretical predictions of FLD have shown that the limitation mainly lies in its many assumptions, some of which are not justifiable or lack proper experiment verification. Industrial applications such as sheet stamping require a simple, accurate and rapid approach to evaluate the FLD.

On the experimental approach, sheet specimens are subjected to a variety of strain paths by a hemispherical punch stretching process. The major-minor strain pairs from the grids that are closest to the neck (Figure 1) on multiple specimens are then utilized to construct a boundary between safe and unsafe zones, which results in the FLDs. Experimental methodology using grid selection and classification in the vicinity of the neck and strain measurement in the neck region is often time consuming. Also, the FLD of aluminum alloy is significantly influenced by the pre-strain [10]. Therefore, in order to obtain a good understanding of the forming behaviour of the aluminum alloy AA6111-T4, a new method incorporating the FE modelling with experimental approach is proposed in this research.

FIGURE 1. A dome test specimen with grids showing a ring of localized neck.
METHODOLOGY

Current research is aimed to develop an approach to obtain FLDs utilizing experimentation of the strain mapping technique for validation (Figure 2). This approach gets away from any experimental strain measurement in the vicinity of the neck on the dome specimens. The FE method has been employed for prediction prior to the specimen preparation and interpretation of the scenarios expected in the experiments.

![MTS console](image1.png)  
![ARAMIS console](image2.png)

**FIGURE 2.** Universal test system MTS with new die design and strain imaging system ARAMIS using CCD camera.

**Experimental**

A hemispherical dome test rig using a 4” standard Nakajima test punch was designed and commissioned with an instrumented and controlled two-actuator mechanical test system. The stretching experiments were performed at a speed of 0.05 in/s.

Experiments were carried out using hemispherical dome tests for a range of geometries by varying specimen widths and friction between the punch and the sheet to obtain various strain paths (Figure 3). All specimens have a uniform length of 6.5”. To obtain the strain paths in the negative strain plane in the FLD map, strip specimens with width of 0.5” (referred to standard ASTM B557M-94), 2”, 4” were used, whereas 6.5” width specimens with various lubrication conditions, such as dry, grease, Teflon, were used to obtain strain paths in the positive strain plane.

**FIGURE 3.** Various specimen geometries.

The specimen profile for the shear test was designed by modifying the ISO 11003-2 (ASTM D 3983-81) [11]. It was assumed that both the clearance (C, length between the notch tips) and spacing (S, length between the notch body) influence the strain ratio \( \beta \) (Figure 4). Strain path of pure shear is practically impossible in a hemispherical punch test due to the out-of-plane deformation. A profile of two non-symmetric rectangular notches of 1mm was designed to obtain a strain path that approaches \( \beta = -1 \) as close as possible by varying the clearance and spacing.

**FIGURE 4.** Specimen profile designed for the shear test in the hemispherical dome test.

Configurations of different notch length and spacing were predicted in the FE modelling and verified in experiments.

**Computational / FE**

There are three major objectives in the FE simulations:

1. The formability data was collected from the FE simulations of hemispherical punch tests in which various combinations of specimen geometry and friction produce different strain paths, and then were assembled to construct an FLD.

2. The complete process, including clamping process from the upper die and dome stretching from the punch, was simulated in the FE modelling due to the pre-strain influence during the clamping stage.

3. A wider range of possible combinations of notch width and length parameters was tested in the FE simulation. These parameters were modified to obtain different specimen profiles for the determination and optimization of the ideal configuration that is closest to a strain path of shear. This prediction provided the reference for the specimen preparation.
The finite element program, ABAQUS, was used as the analysis tool. A 3D model was utilized. The limit of the dome height for different specimen configurations was simulated. Suitable FE simulation models were developed by employing the suitable yield criterion, hardening laws, friction, etc.

**Validation**

Validation of the predicted FLD was obtained with the variation in the strain distribution field during deformation utilizing the ARAMIS® optical strain mapping system. The mechanism of this strain imaging technique is that the speckle deformation instead of grid pattern is employed in tracking the evolution of the dome surface. A water-based ink is painted on the surface of the specimen as black and white speckle patterns, which can be continuously captured by the camera of ARAMIS system. Images at regular intervals can be analyzed and computed to output the strains of the deformed speckles.

**RESULTS AND DISCUSSION**

The capacity of the on-line strain imaging system was investigated because this technique produces the competent results to validate the assumptions utilized in the FE analysis. In a given test of a 6.5” specimen with dry condition, a path was selected from the pole to the edge (near the draw bead) of the dome surface so that the zone of localization was covered. Strains of the speckles along this path were tracked (Figure 5).

![Figure 5](image5.png)

**FIGURE 5.** A strain map of a dome test specimen with a band of localization calculated in ARAMIS.

The strain history of the selected path is re-plotted in Figure 6. The zone of localization was clearly located, where the magnitude of the strain was also present. The loading condition, or the lubrication condition can be identified, since generally the occurrence of localization moves from edge to the pole as the lubrication improves. Also, the fracture strain can also be obtained if the sampling rate of imaging is adjusted to a faster one.

![Figure 6](image6.png)

**FIGURE 6.** A map of strain history calculated in ARAMIS for the dome test specimen in Figure 5.

By utilizing the on-line strain imaging technique, some forming characteristics can be captured continuously even when the deformation is minor, such as the strain received during the clamping process of the hemispherical punch test, a grid layout of strain map shown in the Figure 7. Although the strain found at this stage was less than 0.02, it has already introduced a pre-strain, which has to be considered in the later construction of FLD, since this type of pre-strain is generally tension before the dome test. For a partially clamped 0.5” specimen, pretension will decrease the formability in the same orientation. A biaxial pretension of a fully clamped specimen will also lower a little bit the forming limit curve away from the one of as-received material. Therefore, despite the difference in the geometry, a tension received in the clamping stage will result in a lowered FLD.

![Figure 7](image7.png)

**FIGURE 7.** Strain map captured by ARAMIS in the clamping process.

This phenomenon was simulated with good agreement in the FE modelling (Figure 8). However,
this was only pronounced in the strip specimen. In the case of a round specimen with uniform extra material that can be fully clamped by the draw bead, the grid layout was not so marked. Experimental investigation is required to verify if this observation from the FE prediction is geometry dependent. The reason that the strain layout in the strip specimen is not axi-symmetric may be due to the square geometry. Material flow from the four vertices is not restrained as those from the middle edge of the specimen, where wrinkling generally occurs. Furthermore the FE investigation should be carried out if the grid layout of strain still occurs when the square specimen has excessive material outside the draw bead.

The implication of this observation of the pre-strain during the clamping process can be mainly associated with the design of the draw bead, or, clamping control, either load control or position control, since a pre-strain is inevitable during the clamping process. The draw bead should be locked tightly during the dome test to prevent unnecessary material flow. Meanwhile, the clamping force during the dome test should not be offset by the punch force. Empirically, position control of the die or blank-holder can be taken to minimize the magnitude of the pre-strain.

The shearing test with biaxial loading rig was a novel approach in this research to obtain a wider range of strain path that is close to the pure shear path $\beta = -1$. The FE work preliminarily predicted a series of configurations for specimen preparation. It showed that the negative clearance produced a closer path to pure shear than the case of positive clearance. Given the negative clearance, as the notch spacing decreases, the strain ratio $\beta$ decreases, which is closer to $\beta = -1$.

Figure 9 presents the FE predictions for the distribution of the equivalent plastic strain prior to the dome test, or the pre-strain received during the clamping process. It can be seen that the shear band has already formed and this amount of strain should be taken into account in the strain path for FLD construction. The FE results are in reasonable agreement with the experiment and that from ARAMIS measurement (Figure 10).

<table>
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<tr>
<th>No.</th>
<th>Notch Length L</th>
<th>Clearance C</th>
<th>Notch Spacing S</th>
<th>Notch Ratio C/S</th>
<th>Strain Ratio $\beta = \varepsilon_2 / \varepsilon_1$</th>
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</table>

Note: $t$ – Thickness of the sheet, 1mm; $n$ – Width of the notch, 1mm; $W$– Width of the specimen, 12.7mm.
Experimental results verified the FE predictions of shear specimen design. Figure 11 shows the typical characteristics that are commonly obtained in the trimming test. The trajectory of the crack path with the S-shaped form in the left image represents the case of small clearance. The tip of the crack lies in a localized neck cavity in the middle of the notch width. The right image is the case of large clearance, in which the crack path propagates in the shear bands to form a trajectory of biconvex shape.

Further experiments are required to capture the strain path change in different configurations of shear specimens, since the FE prediction has shown that as the notch ratio decreases from minus to -1, the strain path changes from shear to tension then fracture while as the ratio decreases from plus to +1 the specimen is subjected to tension then shear and fracture.

CONCLUSIONS

The proposed method of incorporating the on-line strain imaging technique with the FE prediction to obtain the formability characteristics of automotive sheet materials produced good results and reasonable agreement. The ARAMIS strain mapping system can be utilized as a measure to validate the FE prediction. Strain contours from the specimen can be obtained from the speckle evolution other than the traditional grid system, which provides a faster approach to obtain strain path to construct the FLD.

Pre-strain during the clamping process was captured and studied in both the experimental and the FE simulation method, which could be used for the analysis of possible deviation in FLDS, and provide reference for tool setting and process control.

The specimen profile with non-symmetric notches designed for shearing tests in the hemispherical dome test was investigated in the FE prediction and verified in experiments using the on-line strain imaging system. By varying the notch length and spacing, a wider range of strain path that is close to the pure shear path can then be obtained.

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REFERENCES