Influence of anisotropy evolution on strain path independent failure limits

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Abstract. Stress based forming limit diagram (SFLD) and polar effective plastic strain (PEPS FLD) diagram are two techniques reported to be independent of strain path change. Thus, these techniques are capable of predicting failure in pre-strained sheet metal samples. Therefore, in this study evolution in anisotropy properties of sheet metals were considered in terms of evolution in yield shape during conversion of conventional strain based forming limit diagram (FLD) to SFLD and PEPS-FLD. The evolution in anisotropic properties were modelled as a function of effective plastic strain depending on which the anisotropic coefficients of non-quadratic yield model Yld2000-2d were calculated. Further, to analyse the strain path change effect, metal sheets of extra deep drawing quality steels were first deformed under biaxial condition in Marciniak in-plane stretch forming setup. The pre-strained samples were subsequently deformed with hemispherical punch till the necking appears. For failure prediction, finite element modelling of the complete procedure was performed considering evolution in the yield shape. Finally, both the failure criteria were implemented for failure prediction. Implementation of the evolution in yield function in finite element analysis and failure criteria provided better results.

1. Introduction
Sheet metal forming is an integral part of automotive industries due to manufacturing of various auto mobile body parts like car fender, A, B, C pillars, roof, bonnet etc. The increasing aesthetic requirements associated with car design also increasingly making the sheet metal forming complex to obtain the desired final product without any failure. Concern over car emission, fuel efficiency also led to application of different light weight metallic alloys. Many times, the newly introduced lightweight materials are not easy to form and specific arrangements are required. Hence, recent research activities in the field of sheet metal forming is directed toward either development of more flexible forming techniques or to enhance theoretical understanding of the material behaviour during forming to increase the extent of formability. For the theoretical investigation numerical simulation is a reliable and effective tool which reduces the requirement of large number of experimentation and thus saves resources and human effort. In case of finite element (FE) simulation, the information related to specific material is modelled based on the mechanical properties of the material such as elastic modulus, Poisson’s ratio, density, yield function and hardening parameters. The yield function defines the elastic limit of the material and normally serves as the plastic potential. In general, the coefficients of yield function are
estimated based on plastic anisotropy parameters, and the yield stress is treated to be constant throughout the deformation process. Further, size of the yield function is assumed to be increased proportionally with strain hardening while keeping its shape constant with the assumption of isotropic hardening. However, recent development in the field of metal plasticity revealed that anisotropy properties of the material changes with plastic deformation. Zamiri et al. [1] incorporated change in R-values due to deformation was into FE simulation to improve prediction accuracy. Wang et al. [2] incorporated changes in stress ratio along different anisotropic direction into FE simulation by expressing yield function in terms of effective plastic strain. A fourth order polynomial function was utilised by Safaei et al. [3] to demonstrate the evolution in directional stress ratio. However, not only the evolution in the anisotropic properties but also proper failure criteria need to be utilised for accurate prediction of the forming behaviour. Mostly strain based forming limit diagram (FLD), estimated either from experimentation or by theoretical approach, is implemented as the failure criterion. Requirement of obtaining complex parts needs multiple forming step. It has been well established that strain based FLD depends on strain history of the blank material. Therefore, after each forming operation a new FLD must be calculated for prediction of the formability in subsequent step. Hence, in case of theoretical estimation of FLD, strain path change need to be considered. Considering the huge experimental effort or the complexity in the calculation to make strain FLD applicable for multistep forming, several other theoretical approaches were explored by different researchers. Among them stress based FLD and polar effective plastic strain (PEPS) based FLD diagrams are the most popular approaches. The concept of stress based FLD (SFLD) was popularised by Stoughton [4]. It was reported that SFLD does not depend on deformation history if the amount of pre-strain remain relatively lower (<0.1) [5]. The path independent nature of SFLD was challenged by Yoshida et al. [6] and it was found that SFLD remains path independent if unloading takes place between subsequent deformation step. The effectiveness of PEPS FLD diagrams was established by Yoon and Stoughton [7].

In the present work, a representative study is presented where influence of evolution in anisotropy parameters are incorporated into prediction of SFLD and PEPS FLD. Evolution in the yield shape is also incorporated into FE simulation for enhancing the accuracy in failure prediction of the material. Both SFLDs and PEPS FLDs are used to predict the formability of pre-strained samples and a comparative study is presented here to highlight the effectiveness of incorporating the evolution in anisotropic parameters of material in both FE simulation and failure criterion as both criteria is path independent in the domain of the study.

2. Methodologies

2.1. Evaluation of mechanical properties of the material

The Uniaxial tensile testing on extra deep drawing quality (EDD) steel sheet (1.2 mm thickness) were performed along three material directions i.e. rolling (RD), transverse (TD) and diagonal direction (DD) to obtain the mechanical properties as shown in Table 1. The Lankford anisotropy parameters (R-value) along different anisotropic directions were also calculated using the relation $R = \frac{\varepsilon_w}{\varepsilon_t}$ where, $\varepsilon_w$ and $\varepsilon_t$ are the true width and thickness strain, respectively. Stack compression tests were performed to assess the stress-strain relationship and R-value like parameter, $R_{BB} = \frac{d\varepsilon_{RE}}{d\varepsilon_{RD}}$, of the material in balanced biaxial condition. It is mostly observed that the stress ratios along different directions varies with increase in plastic strain. However, variations in R-values and strain rate sensitivity of the material were neglected.
Table 1: Mechanical properties of the selected materials

| Direction | Yield strength (MPa) | Ultimate tensile strength (MPa) | Uniform elongation (%) | R value | K value (MPa) | n | $\varepsilon_0$ |
|-----------|---------------------|-------------------------------|------------------------|---------|--------------|---|----------------|
| RD        | 262.7               | 414.9                         | 21.25                  | 1.56    | 626.5        | 0.22 | 0.005          |
| DD        |                     |                               |                        | 1.47    | 622.8        | 0.21 | 0.006          |
| TD        |                     |                               |                        | 1.71    | 631.2        | 0.21 | 0.005          |
| BB        |                     |                               |                        | 1.11    | 618.2        | 0.19 | 0.006          |

2.2. Two-step forming

Square blank with dimension of 200 mm × 200 mm were trimmed out from the as received EDD sheets and the blanks were deformed in an in-plane stretch forming set up. In case of in-plane stretch forming, a flat bottom punch of diameter 101.6 mm was used to stretch the blank clamped under draw bead with a diameter of 150 mm. The blank was deformed until it showed an average strain (principal strain) of 5% on the surface. The average strain at the bottom of the deformed blank was measured by grid marking analysis. The actual punch displacement to obtain 5% strain was calibrated after rigorous FE simulation. Subsequent to the in-plane stretching, a circular blank with a diameter of 90 mm was taken out from the flat portion of the stretched blank for further deformation under a hemispherical punch. In this second stage of deformation, punch diameter was kept 50 mm with a die opening of 54 mm and the blank holding force was 132 kN. Detailed discussion on the two-stage forming set is available in Basak and Panda [8]. Different strain path was followed in the second stage of deformation and corresponding sample geometry was fabricated from the 90 mm blank. The deformed blank after each stage of deformation is shown in Figure 1.

![Figure 1: Deformed pre-strained specimens](image)

2.3. Stress based forming limit diagram

The stress based FLD or SFLD maps each point in the strain based FLD to the stress space. The pair of limiting strain is selected from strain based FLD following a particular strain path and strain ratio is calculated ($\rho = \frac{d\varepsilon_2}{d\varepsilon_1}$). The strain ratio can be related to the stress ratio ($\alpha = \frac{\sigma_2}{\sigma_1}$) through the selected yield function. A parameter $\xi$ is defined as the ratio of the effective stress to the major stress ($\xi = \frac{\bar{\sigma}}{\sigma_1}$) and can be expressed using yield function. For plane-stress condition, the parameters $\alpha$, $\xi$ and $\rho$ can be correlated with effective strain following the plastic work equivalence.

$$\bar{\varepsilon} = \frac{\varepsilon_1}{\xi} (1 + \rho \alpha).$$  

With effective plastic strain determined from the equation, effective stress can also be estimated using any isotropic hardening law. Therefore, the major and minor stress can be estimated using parameters $\alpha$ and $\xi$. However, if evolution in anisotropy is considered then the complete set of equations need to be calculated iteratively as yield function itself becomes a function of effective plastic strain.

2.4. Polar effective plastic strain diagram

Effective strain falls under the category of stress metric as it is uniquely related to stress tensors, thus independent of the path change effect. Hence, Stoughton and Yoon [9] proposed a limiting curve to be...
plotted in a polar diagram and termed as polar effective plastic strain (PEPS) based FLD. The x-axis of the diagram was defined as \((\bar{\varepsilon} \times \sin \theta)\) and y-axis was defined as \((\bar{\varepsilon} \times \cos \theta)\) where, \(\theta = \tan^{-1} \frac{\varepsilon_2}{\varepsilon_1}\). In the present study, effective plastic strain data were collected for each strain path of the FLD during the conversion of FLD data to SFLD. The angle \(\theta\) is also obtained from the strain ratio of a particular strain path and PEPS FLD diagrams were plotted. As the estimation of PEPS FLD relied upon calculation of effective plastic strain as demonstrated above, evolution in anisotropy was already implemented.

2.5. Finite element simulation

Commercial explicit FE software package LSDYNA was utilized in the study. Quarter symmetric models were prepared for each step of the two-step forming operation. The tools were modeled as rigid body as per the dimensions of the original tools. The blanks were modeled with Belytschko–Lin-Tsay shell elements. Yld2000-2d was used as the yield function to model the material along with Swift’s hardening law. In the study, evolution in anisotropy parameters were implemented by treating the coefficient of the yield function as functions of effective plastic strain. Therefore, with every increment in effective plastic strain the directional stress ratio was recalculated based on which yield coefficients were evaluated. Hence, instead of constant yield coefficient evolving set of yield coefficients were used. The FE simulation performed considering evolution in anisotropy parameters is termed as EVO_FE and the FE simulation the evolution in anisotropy not incorporated in yield function is termed as NONEVO_FE.

3. Results and Discussion

3.1. Application of stress based FLD

![Strain distribution](image)

Figure 2 Comparison of strain distribution over the surface of samples deformed in the second stage after 5% equi-biaxial pre-strain in first step: (a) SP1, (b) SP3.
The major and minor strain distributions, over the deformed dome surfaces of pre-strained EDD sheet materials, were predicted from the FE simulation for the similar LDH. Strain distributions predicted by both EVO_FE and NONEVO_FE were correspondingly validated with the experimental results in Figure 2. These strain distributions were plotted with respect to the deformed dome center referred as a pole. It was found that the numerical value of the peak strain (major strain) was highest for SP1 specimen. From the minor strain distribution, it was evident that the minimum minor strain was positive for all the cases including the SP3 specimen. This is attributed to the biaxial pre-strain of the samples. It was also found that the maximum strain was induced at a certain distance from the pole where the punch lost contact with the sheet metal during deformation. Over the punch friction restricted thinning of the material. However, at the punch detaching point the material got stretched, and hence more strain was observed. The excellent correlation between the experimental and EVO_FE predicted strain distributions indicates the reliability of the developed FE model in the present work. The strain distribution predicted by NONEVO_FE could not follow the experimentally observed trend as compared in Figure 2. For the simulations with NONEVO_FE, both major and minor strain distributions could not be predicted for the SP1, while the major strain was considerably underestimated at the distance of 5 mm from the pole for the SP3. The enhanced accuracy of EVO_FE is attributed to the fact that in can accommodate the evolving shape of yield surface with increase in plastic strain. It is observed that yield surface becomes blunter at the balanced biaxial condition delaying the change of strain state to plane strain condition. As EVO_FE resulted better prediction in strain distribution over the deformed surface of the pre-strained samples, in the next sections discussions were kept limited to EVO_FE only.

3.2. Application of stress based FLD

In this study, an experimentally obtained strain based FLD of EDD steel reported by Basak and Panda [8] was converted to SFLD according to the methods described in section 2.3 incorporating anisotropic evolution in yield function. To differentiate the estimated SFLD from SFLDs calculated without evolution in yield surface, the SFLD was termed as EVO_SFLD. The EVO_SFLD was implemented for failure prediction of pre-strained samples. In case of implementation of SFLD in failure prediction, element stress data were collected from the simulation and superimposed on the SFLD curves (Figure 3a) as SFLD cannot be directly incorporated in LS-DYNA. The predicted LDHs are shown in Figure 3b. It is shown that EVO_SFLD rather under-predicted the LDH in case of lubricated biaxial specimen (SP1) though LDH is predicted accurately for other two sample geometries.

![Figure 3 a) stress path of pre-strained specimen in SFLD, b) Comparison of LDH predicted with SFLD](image)

3.3. PEPS FLD

The PEPS FLD was also implemented to predict the failure during the second step deformation of the blanks under hemispherical punch. The critical elements were identified and the corresponding major
and minor strain data were collected with regular interval. The major and minor strain data were then converted to points at PEPS space. Figure 4a depicts the strain path of the blanks in second stage of deformation superimposed within a PEPS FLD. It was observed that LDH was predicted for the SP1 and SP3 samples reasonably well (Figure 4b). However, it was observed that LDH was slightly over predicted for the case of SP2.

Figure 4 a) stress path of pre-strained specimen in SFLD, b) Comparison of LDH predicted with SFLD

4. Conclusion

In this study evolution in yield function was extended to estimate stress based FLD and polar effective plastic strain based FLD. Both of these failure criteria do not depend on the strain path history and robust in nature to predict formability in multi-stage forming. Hence, stress based FLD and PEPS FLD incorporating evolution in yield function were implemented to predict the formability in terms of LDH in multistage forming. The following conclusion can be inferred.

1. Evolution in yield function was successfully incorporated in estimation of SFLD and PEPS FLD. Both SFLD and PEPS FLD were successfully implemented to predict failure in two step forming.

2. The LDH predicted with SFLD corroborated well with experimental results for all three specimens SP1, SP2, SP3. However, PEPS FLD slightly over predicted the LDH in plane strain condition for specimen SP2.

3. The predicted strain distribution over the deformed surface by EVO_FE followed the experimental trend properly.

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