EFFECT OF ANISOTROPIC YIELD FUNCTION EVOLUTION ON ESTIMATION OF FORMING LIMIT DIAGRAM

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Abstract. In case of theoretical prediction of the FLD, the variations in yield stress and R-values along different material directions, were long been implemented to enhance the accuracy. Although influences of different yield models and hardening laws on formability were well addressed, anisotropic evolution of yield loci under monotonic loading with different deformation modes is yet to be explored. In the present study, Marciniak-Kuczynsky (M-K) model was modified to incorporate the change in the shape of the initial yield function with evolution due to anisotropic hardening. Swift’s hardening law along with two different anisotropic yield criteria, namely Hill48 and Yld2000-2d were implemented in the model. The Hill48 yield model was applied with non-associated flow rule to comprehend the effect of variations in both yield stress and R-values. The numerically estimated FLDs were validated after comparing with FLD evaluated through experiments. A low carbon steel was selected, and hemispherical punch stretching test was performed for FLD evaluation. Additionally, the numerically estimated FLDs were incorporated in FE simulations to predict limiting dome heights for validation purpose. Other formability performances like strain distributions over the deformed cup surface were validated with experimental results.

1. Introduction

Accurate prediction of sheet failure during sheet metal forming simulation is crucial for automotive stamping industries to enhance the productivity in the design stage. Over the decades, numerous experimental methods were reported for estimating the limiting strain that a material can sustain during forming in terms of forming limit diagram (FLD). Experimental evaluation of FLD is mainly performed deforming sheet metals of specific geometries over a punch, and measuring major and minor strain at the onset of necking or splitting. In this context, various sample geometries [1-3] and punch design were proposed [4,5] over the decades. However, the experimental procedures for evaluating FLDs are still very time consuming and painstaking. Unavailability of advanced equipment like DIC sometimes demands sufficient expertise of the operator for obtaining ample points to draw a reliable line. Because
of this reasons, many theoretical models to estimate FLDs of a material were developed [6,7]. The most attention was showed on the model proposed by Marciniak and Kuczynski (MK model) [8] in the academic and research community. Works were reported with several beneficial improvements in the original MK model to make the model more general [9,10]. Studies were well reported on the influence of different yield criteria on the estimated FLD incorporating MK model [6,11]. However, all these research only considered the initial directionality in yield strength and R-values for calculating the respective coefficients in the yield function along with isotropic hardening law. Recent researches showed that initial anisotropy measurement of sheet metal i.e. variations in yield stress and R-values along different material directions evolves with amount of plastic deformation [12,13], and hence, initial shape of yield locus evolves with increase in plastic strain.

In the present work, FLD of a low carbon steel was estimated using MK model incorporating anisotropic hardening model coupled with Hill48 and Yld2000-2d (Yld2k) yield theory to investigate the influence of anisotropy evolution on estimation of limiting strain. The estimated FLD was validated with experimentally evaluated FLD. Further, evolutionary anisotropy was implemented in FE models for simulation of punch stretching test to predict limiting dome height (LDH) and strain distribution over the deformed dome for validation purpose.

2. Experimental procedures

2.1. Evaluation of mechanical properties

The uniaxial tensile test was conducted on the selected steel with highly textured microstructure to assess the mechanical properties as shown in figure 1. Specimens were extracted from the sheet metal at different angles [0°, 45° (DD), 90° (TD)] with rolling direction (RD) to measure anisotropy of the material. Hydraulic bulge tests were also performed for getting data for balanced biaxial condition (BB). Extensometer was employed to record stress-strain responses of the samples. Swift’s hardening model was incorporated to calculate strength coefficient and strain hardening exponent from the true stress–true strain response of the material. Strain rate sensitivity of the material was neglected as all the tests were conducted in quasi static condition and in room temperature. The R-values of the material were measured as 1.425, 0.995, 2.124 and 1.023 along RD, DD, TD and BB direction respectively. The detailed descriptions of the experimental procedures can be found in [12]. The evolution in R-values with deformation were negligible and hence, not considered here.

![Figure 1. Comparison of true stress–true strain responses of the material along different material direction.](image-url)
2.2. Experimental evaluation FLD

Five specially designed samples were stretched over a Φ50 mm hemispherical punch till the onset of the localized necking with different combination of lubrication to achieve six different strain path (i-vi) ranging from tension-tension to tension-compression region. Circular grid analysis was employed to measure the major and minor surface strain of the necked, fracture and safe ellipses over the deformed domes as discussed in previous literatures [14-16]. The deformed domes with specific geometries and the corresponding strain points are depicted in Figure 2 a) and b) respectively. The FLD was plotted through the maximum safe strain points as can be observed in figure 2b). The limiting dome heights (LDH) of the deformed samples were measured using height gauge and the same was discussed.

3. Constitutive Modelling

3.1. MK method

The MK model considered presence of imperfection or inhomogeneity in the material which was demonstrated as a groove with lower thickness than that of the parent metal, and was represented as inhomogeneity factor (equation 1) in the model. Stress and corresponding strain development in the homogenous region was calculated applying theory of plasticity, and the stress-strain developed in the groove region was estimated using strain compatibility condition and force equilibrium. The failure assumed to occur whenever ratio of strain increment in principle axis in the homogenous region to the groove region drops below a critical value (0.1), and the principle strains at the homogeneous regions at this instant were considered to be the limiting strain of the material. In the present study, Hill48 and Yld2k (yield exponent 6) were considered as yield functions along with Swift’s hardening law. In general, the coefficients of any yield functions (H, F, G, N for Hill48, and α4 to α8 for Yld2k) are estimated from the initial anisotropy measurement of the material i.e. four yield stress values and/or four R-values, and shape of the yield loci is considered to be remain constant, and isotropic hardening is implemented to model the increase in yield loci size for addressing the work hardening of the material. However, the coefficients of yield functions were treated as function of equivalent plastic strain in the present study using anisotropic hardening to incorporate change in initial yield locus shape due to evolution of directionality in yield strength with plastic deformation. Hence, both the shape and size of
the yield locus were recalculated as a function of equivalent plastic strain at each iteration for satisfying
the consistency condition, to update stress-strain. FLD estimated implementing evolutionary anisotropy
were termed as MK FLD_Evo. In case of Hill48 non-associated (Hill48 NA) flow rule was adapted to
incorporate both anisotropy in yield strength and R-values.

3.2. FE modeling
FE simulations were performed in LS DYNA platform for prediction of LDH and strain distribution
over the dome height. Tooling were modeled as per the punch stretching test set up and assumed as rigid
body in simulation. Blank was modeled with shell element considering the thickness of the steel sheet.
Coulomb’s friction model was implemented between tooling and blank with friction coefficient of 0.15
for dry condition and 0.01 for lubricated condition. Constitutive modeling incorporating evolutionary
anisotropy as mentioned before for both the yield functions (Yld2k and Hill48 NA) were implemented
through user material subroutines UMAT. The failure was predicted after incorporating estimated FLDs
from MK model and FLD evaluated experimentally. The predicted results were validated with
experimental results. The FE simulations with evolutionary model were referred as EvoFE throughout
the paper.

4. Results and discussion
The estimated FLDs applying MK model keeping $f_0 = 0.999$ are shown in figure 3. In case of Yld2k,
MK FLD_Evo was closer to the experimental FLD, particularly in the tension-tension region. Without
incorporation of evolutionary anisotropy, MK model with Yld2k predicts very low limiting strain at
biaxial stress state. This can be attributed to the shape of the yield locus. Being non-quadratic the
transition of biaxial stress state to plane stress state is quite sharp in Yld2k and hence, low limiting strain
was predicted. However, with evolutionary anisotropy, yield locus was less sharp with increase in plastic

Figure 3. Estimated FLD with plane MK model and MK model incorporating anisotropic hardening
a) Yld200-2d b) Hill48.

deformation and delays failure causing higher limiting strain prediction. Incorporation of evolutionary
anisotropy also improved the FLD prediction incorporating Hill48 yield model, though predicted FLD
was much lower compared to the experimental FLD. All the FLDs were incorporated in FE simulations
to comprehend the influence of evolutionary anisotropy in formability prediction. The predicted LDH
were compared with the experimental values in figure 4. Overall, it was observed that EvoFE
incorporating MK FLD_Evo predicted better results. Not only the prediction of LDH but EvoFE
incorporating MK FLD_Evo also predicted the failure location quite properly matching the curvilinear
distance of failure site from pole as can be seen in figure 5. Failure occurred away from the pole as
frictional constrains were significant due to lack of lubrication resulting strain localisation and failure at
the punch-blank detachment point. In case of FE simulations incorporating Hill48, 58% improvement
in LDH prediction (biaxial condition) was observed with incorporation of evolutionary anisotropy, but the predicted results were inferior compared to the results predicted with Yld2k as seen in figure 4.

Figure 4. Comparison of predicted LDH implementing different model with experimental observation for circular sample (dry condition).

Figure 5. Prediction of fracture location for circular specimen (dry condition) implementing Yld2k along with anisotropic hardening.

Figure 6. Comparison of strain distribution over the deformed surface a) circular specimen in dry condition b) sample width 20 mm in dry condition.

The predicted strain paths of the failure element from different FE models were also superimposed on the corresponding FLDs (figure 3). It is observed that predicted strain in biaxial condition is more
for EvoFE, but in tension-compression (width 20 mm) condition the predicted strain was relatively lower for EvoFE than that predicted from conventional FE model. Further, the major and minor strain distribution over the deformed cup were compared for two particular sample geometry in figure 6. In case of circular sample, the predicted strain with EvoFE was close to experimental results compared to that predicted from conventional FE simulation. Prediction in flow strength reduces with incorporation of evolutionary yield locus than that of the non-evolutionary yield locus at biaxial stress state. This resulted enhanced plastic deformation and higher strain prediction in EvoFE. For the samples with 20 mm width also, predicted strain distribution with EvoFE incorporating Yld2k correlated well with experimental results compared to the results predicted with Hill48. This also can be attributed to the difference in prediction of flow strength at the corresponding stress state for different yield model.

5. Conclusions
The evolution of anisotropic yield functions was successfully incorporated as a function of effective strain in MK model for prediction of FLD. The estimated FLDs were close to the experimental FLD. Further, the concept of evolutionary anisotropy was effectively implemented in the user subroutine for LSDYNA. In general, it was observed that FE predicted results improved with incorporation of evolutionary anisotropy compared to conventional FE modelling. It was also observed that strain paths of the failure element predicted after incorporation of evolutionary anisotropy shifts towards right side of the FLD. These observations can be attributed to the difference in flow strength prediction due to incorporation of evolutionary anisotropy. Predicted results with Yld2k showed better correlation with experimental observation than that of Hill48 model. Although non-associated flow rule was considered for Hill48 for incorporating anisotropy in yield strength and R-values, it seems quadratic nature of the yield model could not capture the plastic behaviour of the material.

Acknowledgement
Authors acknowledges supports received from National Research Foundation of Korea (NRF) grants funded by the Korea government (MSIP) (No. 2012R1A5A1048294) and from the Ministry of Trade, Industry and Energy (MOTIE) (No. 10063488).

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