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VALIDATION OF MODIFIED LEMAITRE'S ANISOTROPIC DAMAGE MODEL WITH THE CROSS DIE DRAWING TEST

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Abstract. Dual Phase (DP) steels are widely replacing the traditional forming steels in automotive industry. Advanced damage models are required to accurately predict the formability of DP steels. In this work, Lemaitre's anisotropic damage model has been slightly modified for sheet metal forming applications and for strain rate dependent materials. The damage evolution law is adapted to take into account the strain rate dependency and negative triaxialities. The damage parameters for pre-production DP600 steel were determined. The modified damage models (isotropic and anisotropic) were validated using the cross die drawing test. The anisotropic damage model predicts the crack direction more accurately.

Introduction

Failure prediction of Dual Phase (DP) steels, during forming processes, is posing a challenge in the field of material modeling. The formability of these materials is limited mainly due to damage development [1]. In general, the process of damage development is anisotropic [2,3]. This article focuses on the development of a damage model which can accurately predict failure in advanced high strength steels. For this purpose the Lemaitre's damage models [4] have been modified and validated using a cross die drawing test. The cross die drawing is an appropriate test to check the formability of a material because of the variety of stress states and strain path changes that occur during the drawing process [5].

Modified Lemaitre's Anisotropic Damage Model

Lemaitre's anisotropic damage model is based on the hypothesis of strain equivalence. The damage variable is taken as a second order tensor denoted by $\mathbf{D}$. The damage evolution is defined as a function of the plastic strain rate.

$$\dot{\mathbf{D}} = \left(\frac{\bar{Y}}{S}\right)^{s} \left|\dot{\boldsymbol{\varepsilon}}_p\right| \quad \text{from } \varepsilon_I^p > \varepsilon_D^p \text{ up to } D_I > D_c \text{ where } \bar{Y} = \frac{\tilde{\sigma}_{eq}^2 \tilde{R}_v}{2E}. \tag{1}$$

Where $|\ldots|$ represents the absolute principal values of the plastic strain rate tensor, $\tilde{\sigma}_{eq}$ is the equivalent effective stress, S and s are damage parameters, ε_D^p is the threshold for damage development, D_c is the critical damage value, E is the Young's modulus and $\tilde{R}_v$ is a function of the triaxiality based on the effective stress. Further details of the model can be found in [4].
In this work some modifications are made to Lemaitre's model to improve its accuracy:

1. The damage evolution defined in Eq. 1 gives the same damage development under tension and compression states. This is not true for metals where damage development mainly constitutes of void growth. Therefore the parameter S in Eq. 1 is modified to S_c using a factor u_f for negative hydrostatic stresses.

$$S_c = S \times u_f \quad \text{for} \quad \tilde{\sigma}^H < 0. \tag{2}$$

Selecting a high value of u_f will give negligible damage development under compression.

2. The post localization strain for DP steels increases with increase in the deformation rate [6]. This phenomenon is linked to the temperature rise in the material with increasing strain rates. The temperature rise enhances the ductility and thus reduces void nucleation and allows the voids to grow larger. Hence, the two damage parameters s and D_c are made a function of strain rate to account for the strain rate effect on damage evolution. These functions are selected such that to fit tensile experiments at different strain rates.

$$D_c = D_{c0}\left[\ln\left(1+\frac{\dot{\varepsilon}^p_{eq}}{\dot{\varepsilon}_0}\right)+0.3068\right] \text{ with } D_c=\min\left(D_c,1\right) \text{ and } D_c=\max\left(D_c,D_{c0}\right). \quad (3)$$

$$s = s_0\left[\ln\left(1+\frac{\dot{\varepsilon}^p_{eq}}{\dot{\varepsilon}_0\cdot s_0}\right)+0.6517\right]^{-\frac{1}{s_0}} \text{ with } s=\min\left(s,s_0\right). \quad (4)$$

Where D_{c0} and s_0 are the reference parameters determined at the reference strain rate $\dot{\varepsilon}_0$. These modifications slow down the damage development and initiates fracture at higher damage values for a higher strain rate.

The above mentioned modifications were also made to the Lemaitre's isotropic damage model.

Damage Parameter Identification

There are four damage parameters which need to be determined i.e. ε^p_D, D_{c0}, S and s_0. The fast identification method [4] given by Lemaitre was used to determine these parameters. This methodology uses the data from a tensile test and a low cycle fatigue test. The tensile test was taken at a very low average strain rate i.e. 0.001/sec. This value is the reference strain rate which is used in Eq. 3 and 4. The values obtained from the fast identification methodology are given in Table 1. These parameters are validated by simulating the tensile test at the reference strain rate (Fig. 1). No inverse fitting was used to fit the parameters and the same parameters are used for the isotropic and anisotropic damage models. Von Mises yield criterion was used as the material was found to be almost isotropic. A physically based strain rate dependent isotropic hardening model 'Extended Bergstrom hardening' [7] was used. The parameters for this model were fitted to tensile tests at different strain rates.

Table 1: Damage parameters for DP Steel determined from the fast identification method.

Parameter	ε^p_D	D_{c0}	S	s_0
Value	0.18	0.1789	1.398	2.3

High strain rates tend to increase the post localization strain in DP steels [6]. This behavior is incorporated in the damage model using Eq. 3 and 4. A tensile test was carried out at a higher strain rate i.e. 0.038/sec which gave ~2% higher strain than that achieved from the test at the reference strain rate. This test was then simulated with the same damage parameters given in Table 1. The comparison of the simulations with experiments is shown in Fig. 2. The damage models predicted the failure approximately at the correct maximum strain for this test whereas the simulation without damage over predicts the failure considerably. If Eq. 3 and 4 are not used then the damage models under predict the failure strain.

Validation of the Modified Lemaitre's Damage Model

The damage models are validated using the cross die drawing test. These tests were carried out at an average strain rate of 1/sec. Fig. 3 compares the force displacement curves of the simulations with the experiments. Among the two experiments shown in Fig. 3, one localized (slightly cracked) at a punch displacement of 39.6mm whereas the other did not localize. The simulation without damage clearly shows an over prediction of the critical punch depth whereas the simulation with the damage models predicts localization at ~39mm punch depth. The damage models under predict the critical punch depth when Eq. 3 and 4 is not used. Fig. 4 shows the comparison of the major strain distribution along the section where the maximum principal strains occurs in the experiments. The strain distribution was measured on the inner surface (facing the punch) of the blank. The strain distribution presented in Fig. 4 is taken from the experiment which did not localize at 39.6mm. The strain did not localize for the simulation without damage and thus gives good agreement with the experimental strain. The strains obtained from the simulations with damage are in good agreement throughout the section except for the part where localization took place. The slight crack in the other experiment occurred almost at the same location as predicted by the damage models. This region is found to be under the plane strain condition.

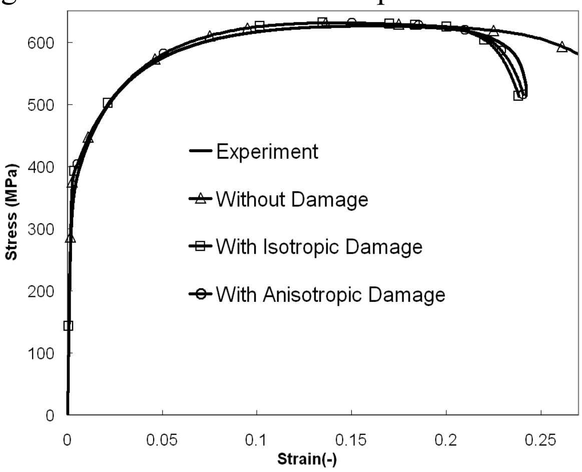


Figure 1: Validation of the damage parameters at reference strain rate tensile test.

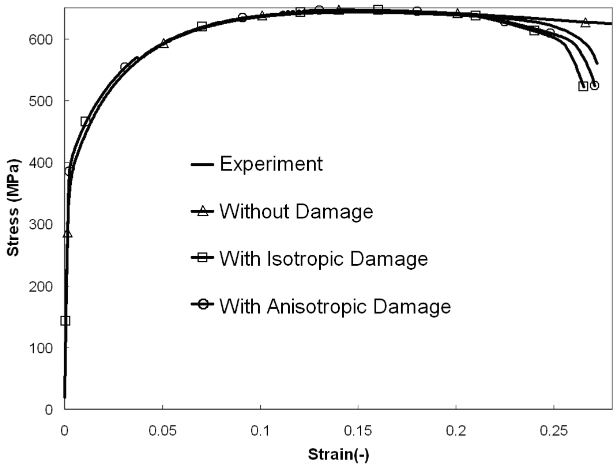


Figure 2: Validation of Eq. 3 and 4 using tensile test at strain rate 0.038/sec

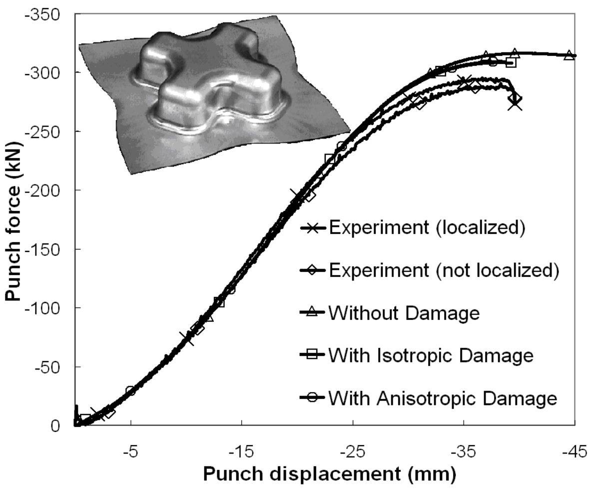


Figure 3: Force-Displacement curve for the cross die test.

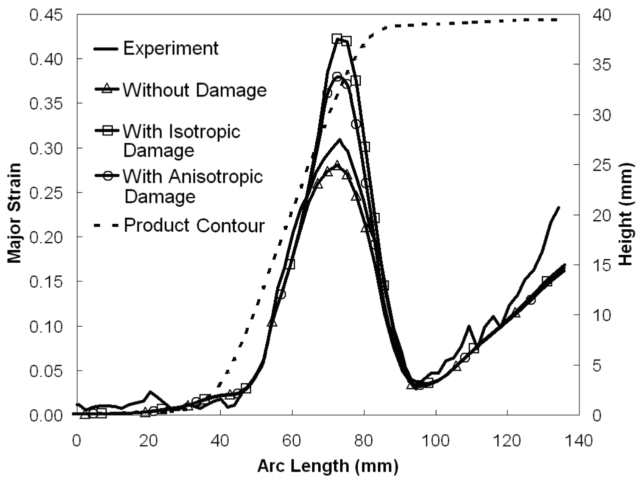
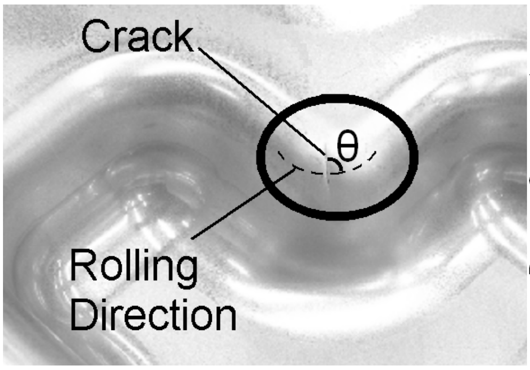


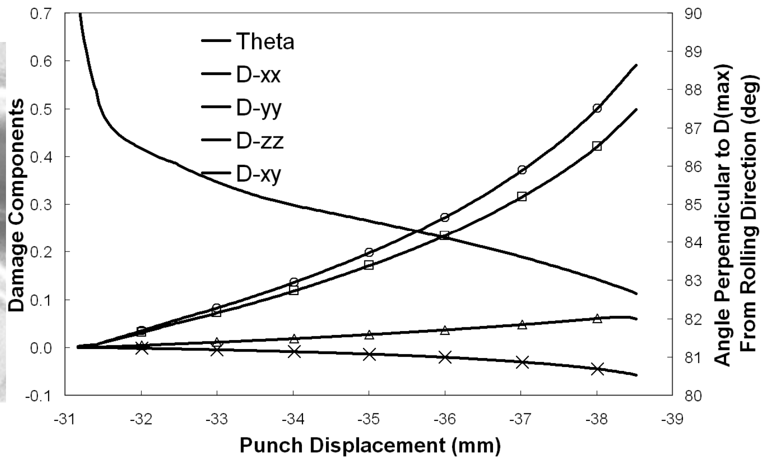
Figure 4: Major strain distribution along the section with maximum strain in the cross die test.

A scalar damage variable is used in isotropic damage model; therefore the information regarding the crack direction can not be obtained from the damage variable. A common approach is to take the crack propagation plane orthogonal to the maximum principal stress direction. This assumption gives inaccurate crack directions if the material undergoes non-proportional load path changes. The crack angle θ, as shown in Fig. 5(a) was determined for the isotropic damage model and the value of θ is found to be ~68^{o}, which is not very accurate. For anisotropic damage, the crack direction can be determined based on the principal damage direction. Fig. 5(b) shows the principal damage direction for anisotropic damage. The crack angle θ is found to be ~83^{o}, which is very close to what is found in the experiments. Using anisotropic damage is clearly advantageous for predicting the crack direction.

Conclusions

The Lemaitre's damage model was modified to take into account strain rate dependency and negative triaxialities. The modified model was validated with the cross die test. The simulation results are in good agreement with the experiments. The crack direction predicted from the isotropic damage model simulation deviates from the experiments whereas the anisotropic damage model simulation predicted the crack direction more accurately. This difference is mainly due to non-proportional strains. All the damage parameters were obtained from uniaxial conditions and were successfully used to predict failure in a forming process with a variety of triaxilities ranging from compression to biaxial conditions. The failure was predicted in a region with plane strain condition at almost the exact critical punch depth found from experiments.





(a) Actual crack orientation. (b) Crack orientation from anisotropic damage model.

Figure 5: Prediction of crack direction.

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