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Effects of anisotropic yield functions on prediction of forming limit diagrams of DP600 advanced high strength steel

Fahrettin Ozturk[a,*], Serkan Toros[b], Suleyman Kilic[c]

[a]Department of Mechanical Engineering, The Petroleum Institute, Abu Dhabi, 2533, UAE
[b]Department of Mechanical Engineering, Nigde University, Nigde 51240, Turkey
[c]Department of Mechanical Engineering, Ahi Evran University, Kirsehir 40100, Turkey

Abstract

In recent years, numerous researchers have reported that the predicted forming limit diagrams strongly depend on the method of determining the material parameters used in the yield functions and the corresponding the shape of the yield surface. In this study, the capability of different yield functions to predict the forming limit diagram of DP600 advanced high strength steel sheet is investigated. Additionally, the effects of determination method of the anisotropic parameters on the forming limit diagram are studied. The yield functions proposed by Hill-48, Barlat-89, and YLD2000-2d are considered and the forming limit diagrams are constructed using the Marciniak Kuczynski model. Results reveal that predictions using different yield functions are lower than the experimental forming limits. In terms of shape and tendency, the YLD2000-2d curve is best suited for representing experimental curve.

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Keywords: DP600; FLD; Yield functions; M-K model

* Corresponding author. Tel.: +971 2 6075197; fax:+971 2 607 5200
E-mail address: fozturk@pi.ac.ae.

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1. Introduction

Reducing car weight and exhaust gas emission have recently been a key targets for automotive industries. Mostly they have been putting a tremendous amount of effort on materials selection of automotive bodies. Therefore, the use of high strength steels which provide higher strength for automobile body parts has been increasing rapidly in sheet metal industry (Kleiner et al., 2006, Kleiner et al., 2003, Neugebauer et al., 2006). One of the typical advanced high strength steels is a dual phase (DP) type steel which is a low carbon steel with soft ferrite and hard martensite. DP steels are annealed by holding the strip in the temperature region for a set period of time and then quenched so that the austenite is transformed into martensite and the ferrite on cooling (Huh et al., 2008). Numerous researches have been carried out for DP steels that satisfy the high strength as well as the high formability. For the successful application of these materials, the formability limitations of the materials must be determined (Keeler, 1994).

Swift and Hill (Swift, 1952, Hill, 1952) developed theoretical models for the instability analysis of materials. Swift developed diffuse necking theory for a biaxially loaded sheet, which is based on the maximum force. The right hand side of the forming limit diagram, where both major and minor strains are positive, is determined via model. Then, Hill proposed the localized necking phenomena which depicts the deformation modes at the left hand side of the forming limit diagram. According to the Hill's theory, localized neck develops along zero elongation direction. The diffuse and localized necking theories are used together in constructing forming limit diagram for all straining modes which vary from uniaxial to biaxial deformation modes. In addition, both of the theories can be applied for the anisotropic materials. Another most commonly used instability criteria that is used for the determination of the forming limit diagram is the Marciniak-Kuczynski inhomogeneity model. In the model it is assumed that there is an imperfection on the material due to the applied rolling operation on the materials prior the forming operation. Derivation of the model formulation and its parameters are conducted to force balance equilibrium for both groove and normal regions.

To predict the forming limit diagram for sheet metal forming under a linear strain path, Banabic et. al (Banabic et al., 2005b) focused on a comparison of different modelling approaches. In their study, orthotropic yield criterion developed by BBC2003 (Banabic et al., 2005a) was used in four models, namely as Marciniak-Kuczynski model, the modified maximum force criterion according to Hora (Hora, 1996), Swifts' diffuse (Swift, 1952) and Hill's localized necking approach (Hill, 1952). Arrieux (Arrieux et al., 1996) studied on the prediction of the onset of necking in deep drawing process by using a numerical method. In the analysis, the forming limit stress surface of a sheet metal was determined based on the Marciniak-Kuczynski model. A comparative study to predict the forming limit diagram was also made by Slota and Spisak (Slota et al., 2005). Three mathematical models (Marciniak-Kuczynski, Hill-Swift, and Sing-Rao) as well as the empirical model by the NADDRG were investigated and their results were compared with the experimental results. As a result of the most of the study, the Marciniak-Kuczynski model shows better agreement with experimental results when compared to the other models. In this present study, the forming limits characteristics of the DP600 advanced high strength steel was investigated via the Marciniak-Kuczynski model. Additionally, in the model, different anisotropic yield functions were evaluated in order to compare the applicability of their results.

Nomenclature

F, G, H, L, M, N	Hill material constants
a, c	Material constants for Barlat-89
K_1, K_2	Invariants of the stress tensor
r_0, r_{45}, r_{90}	Anisotropies in different directions
σ_{ij}^a , σ_{ij}^b	Stress components in safe and groove regions
t_0^a, t_0^b	Initial thicknesses in the safe and groove regions
α_1-α_8	Anisotropy parameters in YLD2000-2d

2. Experimental work and material properties

First, uniaxial tensile tests were applied to 0.8 mm thick sheet samples which were prepared according to the ASTM E8 (ASTM, 2004) standard at 0.0083 s^{-1} strain rate in order to determine the some of the mechanical properties such as anisotropies, yield stress which are used for calculating the yield surface and the forming limit diagram models. All tests were performed using a Shimadzu Autograph 100 kN testing machine with a data acquisition system maintained by a digital interface board utilizing a specialized computer program. Material deformation was measured with a video type extensometer measurement system. Each test was repeated at least three times and their average was used in flow stress–strain curves. The mechanical properties of the material i.e. the yield strength and maximum tensile strength were different for different orientation. The anisotropic coefficients were also calculated for the 15% pre-strain level and the results were tabulated in Table 1.

Table 1. Yield stress, R-value, n, and K for DP600 steel.

Direction	Yield strength (MPa)	R-value	Strain hardening exponent (n)	Strength coefficient (K)
Rolling direction (RD) (0°)	355	0.89	0.194	979.46
Diagonal direction (DD) (45°)	362	0.85		
Transverse direction (TD) (90°)	371	1.12		

Besides the tensile test, the experimental forming limit diagram of the DP600 was also determined via the out of plane formability test (Ozturk et al., 2005). The forming limit diagram experiments were tested by sheet metal formability analysis system. Each test was repeated at least three times or more. To measure the deformation on the samples, square grids which are 2.5 mm × 2.5 mm were performed on the test samples prior the forming operations with a 100 mm hemispherical punch. After the deformation, the deformed grids were measured by Automated Surface Strain Analysis and Measurement Environment and results were plotted.

3. Yield functions

3.1. *Hill's orthotropic yield criterion*

One of the most common yield criteria used in the simulation of forming processes is Hill-48 (Hill, 1948) quadratic yield function which is given as follow.

$$2f(\sigma_{ij}) = F(\sigma_y - \sigma_z)^2 + G(\sigma_z - \sigma_x) + H(\sigma_x - \sigma_y) + 2L\tau_{yz}^2 + 2M\tau_{zx}^2 + 2N\tau_{xy}^2 = 1 \cdot \quad (1)$$

where *F*, *G*, *H*, *L*, *M*, and *N* are the material constants and *x*, *y* and *z* are the mutual orthogonal axes of orthotropy.

3.2. *Barlat-89 yield criterion*

The Barlat and Lian's (Barlat et al., 1989) (denoted as Barlat-89) anisotropic yield criterion is defined as:

$$\phi = a|K_1 + K_2|^m + a|K_1 - K_2|^m + c|2K_2|^m = 2\sigma_y^m,\ K_1 = (\sigma_{11} + h\sigma_{22})/2,\ K_2 = \sqrt{\left((\sigma_{11} - h\sigma_{22})/2\right)^2 + p^2\sigma_{12}^2}\ , \quad (2)$$

where σ_y is the yield stress in uniaxial tension and K_1 and K_2 are the coefficients that are written in terms of the stresses. The anisotropic material constants *a* and *c* are computed based on the measures r_o, r_{45}, and r_{90}. (Details about these parameters can be found in Ref. (Barlat and Lian, 1989).

3.3. *Plane stress yield function Yld2000-2d*

In order to characterize the anisotropic behaviors of rolled sheets, another yield stress surface was described by Barlat et al. (Barlat et al., 2003) for plane stress state denoted as Yld2000-2d. Compared to the previously proposed yield stress functions named as Barlat-89, the new yield stress function has eight anisotropic coefficients which are related with the experimental yield stresses (σ_0, σ_{45}, σ_{90}, σ_b) and anisotropies (r_o, r_{45}, r_{90}, r_b) obtained from the samples prepared in different directions. In here σ_b and r_b values can be obtained under the balanced biaxial tension ($\sigma_{11} = \sigma_{22}$). In the current study, an equi-biaxial yield stress was calculated from the Hill-48 yield function by using the Lankford parameters with assuming $\sigma_b = \sigma_{11} = \sigma_{22}$. Additionally, biaxial anisotropy was determined from the hole-expansion test. In YLD2000-2d the anisotropic yield function can be described as follows:

$$\phi = |\tilde{S}_1' - \tilde{S}_2'|^M + |\tilde{S}_1'' + 2\tilde{S}_2''|^M + |2\tilde{S}_1'' + \tilde{S}_2''|^M,\ \tilde{s}' = C'.s = C'.\mathrm{T}.\sigma = L'.\sigma,\ \tilde{s}'' = C''.s = C''.\mathrm{T}.\sigma = L''.\sigma, \quad (3)$$

where $\tilde{S}_k'$ and $\tilde{S}_k''$ (k = 1,2) are the principal values of the modified deviatoric stress tensor $\tilde{s}$. Here C' and C'' contain anisotropic coefficients and T transforms the Cauchy stress tensor σ to its deviator s. There are eight anisotropic coefficients which are α_1 - α_8 the yield function can be expressed in the isotropic form when all the independent coefficients α_1 - α_8 take as 1. Note that the exponent M has been selected according to the recommendations of Hosford (Hosford, 1972) for B.C.C. metals.

3.4. *Application of M-K model*

In the MK analysis, it is assumed that the pre-existing thickness imperfection in the form of a groove perpendicular to the principal strain directions which means that the angle ψ is equal to 0, the sheet is composed of the nominal area and a weak groove area, which are denoted by "*a*" and "b", respectively.

The initial imperfection factor of the groove is denoted as f_0 and it is defined as the thickness ratio of thickness imperfection to nominal thickness $f_0 = \left(t_0^b / t_0^a\right)$ where "*t*" denotes the thickness and subscript "*o*" denotes the initial state. A biaxial stress state is imposed on the nominal area and causes the development of strain increments in both the nominal (a) and the weak area (b). Necking occurs when the effective strain in the groove area is 10 times of that in the safe area (Butuc et al., 2002a, Butuc et al., 2002b, Cao et al., 2000, Yao et al., 2002). During the entire process, the force equilibrium equations at groove direction must be satisfied as follows:

$$F_{nt}^a = F_{nt}^b, \qquad F_{nn}^a = F_{nn}^b, \qquad \sigma_{nt}^a \exp\left(\varepsilon_3^a\right) t_0^a = \sigma_{nt}^b \exp\left(\varepsilon_3^b\right) t_0^b, \qquad \sigma_{nn}^a \exp\left(\varepsilon_3^a\right) t_0^a = \sigma_{nn}^b \exp\left(\varepsilon_3^b\right) t_0^b, \quad (4)$$

where F_{nn} and F_{nt} are forces in the normal and tangential directions in the groove and σ_{nn} and σ_{nt} are stress components in the ''*n*'' and ''*t*'' directions, t_0^a and t_0^b are initial thicknesses in the safe and groove regions, respectively.

4. Application of anisotropic yield criteria to DP600

In the following, all anisotropic yield criteria described above were applied to DP600 steel sheet. The performances of yield surfaces Hill-48 (Eq. (1)), Barlat-89 (Eq. (2)) and YLD200-2d (Eq. (3)) were checked via the comparison of the anisotropy and yield stress variations with the orientation angle of the grains. Fig. 1 and 2 display the results of variation of the yield stresses and anisotropies with respect to the angle from the rolling direction that obtained by using the Lankford parameters and calibrating the YLD2000 yield criteria by means of the nonlinear least squares method respectively. YLD2000-2d has the best fit with experimental results obtained at different directions when compared the other anisotropic yield criteria due to the characteristics of the function. The increased number of the anisotropic parameters improves the fitting capability of the yield criteria to the experimental result. In the calculation of the anisotropy parameters of the YLD 2000-2d, balanced biaxial yield stress value is necessary. This value was calculated by using the Hill-48 anisotropic yield function for the specific case of the function. The calculated anisotropy parameters are tabulated in Table 2.

Additionally, the yield surfaces of the materials that are obtained for the studied yield criteria were plotted in Fig. 1(c). The models were evaluated for the constant shear stress which is assumed as σ_{12}= 0 in the normalized form.

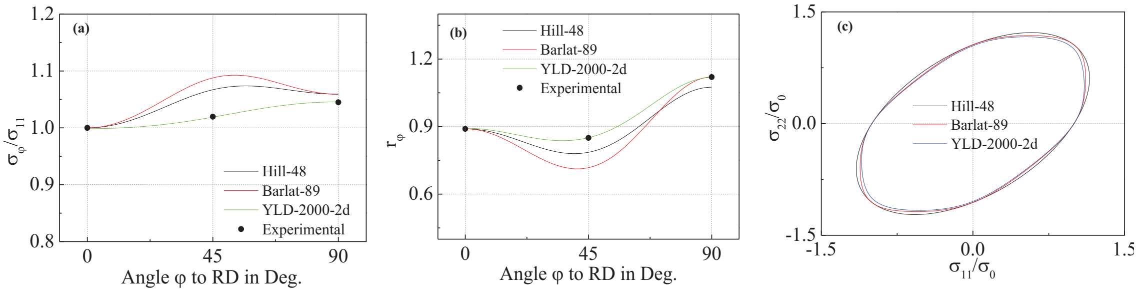

Fig. 1. (a) Comparison of experimental and predicted directional yield stresses for DP600 by parameters identification using the Lankford parameters. (b). Comparison of experimental and predicted directional *r* values for DP600 by parameters identification using the Lankford parameters. (c) .Predicted yield surface contours with Hill-48, Barlat-89, and YLD-2000-2d.

Table 2. Calculated anisotropy parameters for the DP600 steel obtained by the Lankford parameters.

Hill-48	**F**		**G**		**H**		**N**	
	0.3748		*0.5291*		*0.4708*		*1.1125*	
Barlat-89	**a**		**c**		**h**		**p**	
	1.0024		*0.9976*		*0.9441*		*0.9000*	
YLD2000-2d	**α_1**	**α_2**	**α_3**	**α_4**	**α_5**	**α_6**	**α_7**	**α_8**
	1.011	*0.9640*	*1.1910*	*0.9950*	*1.0100*	*1.0180*	*0.9770*	*0.9350*

As can be seen from the Fig. 1(c), the predicted yield surfaces show different behaviours between the models. While the Hill-48 yield function has the broader area for the positive and negative biaxial deformation modes and shear deformation regions, YLD2000-2d more representative model for the experimental results of anisotropies and yield stresses has the narrowest region. After the determining the representability of the yield functions, forming limit diagram of the advanced high strength DP600 steel was determined via Marciniak-Kuczynski model for the studied quadratic and non-quadratic yield functions. The model and experimental results are depicted in Fig.2. During the experimental measurements of the limiting strains on the formed samples, offsetting procedure was performed to the plotted forming limit curve due to the increase the reliability of the measurements and it is assumed as about the 10 %. As can be seen from the figure all models predict the limit strains lower than the experimental values. The predicted value for the plane strain condition is approximately equal to the strain hardening value which is 0.19. In terms of shape and tendency, The YLD2000-2d curve is accord with experimental curve for both left and right hand sides of the forming limit diagram.

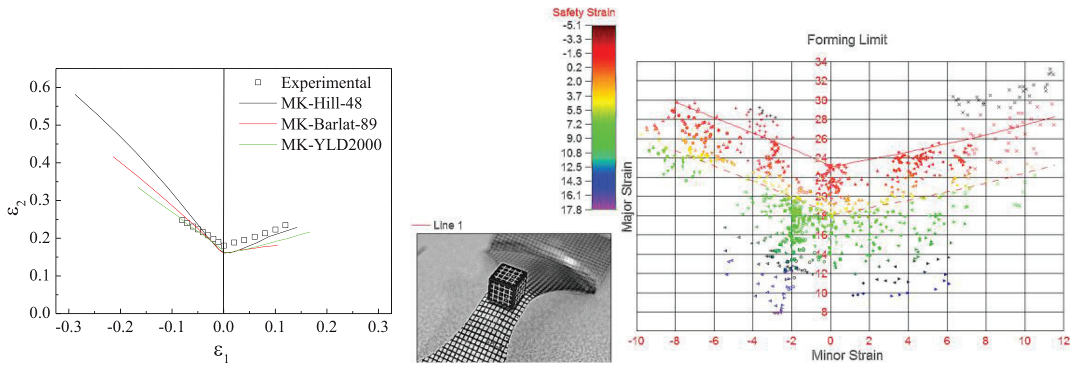

Fig.2. Comparison of forming limit curves for using various anisotropic yield criteria

5. Conclusion

The formability of the advanced high strength DP600 steel was investigated experimentally and numerically. In the numerical works, three different anisotropic yield criteria Hill-48, Barlat-89, and YLD2000-2d were implemented into the Marciniak-Kuczynski model in order to predict the forming limit diagram of the DP600 steel. Results indicated that all anisotropic yield criteria predict the limit strains for the different strain ratios are lower than the experimental forming limits. In terms of shape and tendency, the YLD2000-2d curve is the closest to the experimental curve.

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