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Prediction of forming limit diagram of automotive sheet metals using a new necking criterion

PHAM Quoc Tuan [1,a *], ISLAM Md Shafiqul [1,b], SIGVANT Mats[1,2,c] and CARO Perez Lluis [3,d]

[1]Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona 37141, Sweden

[2]Volvo Cars, Department 81110 Strategy & Concept, Olofström, Sweden

[3]RISE Research Institutes of Sweden, Component Manufacturing Unit, Olofström, Sweden

[a]quoc.tuan.pham@bth.se, [b]shafiqul.islam@bth.se, [c]mats.sigvant@bth.se, [d]lluis.perez.caro@ri.se

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Abstract. A theoretical model for predicting the forming limit diagram of sheet metal, named MMFC2, was recently proposed by the authors based on the modified maximum force criterion (MMFC). This study examines the application of MMFC2 for two automotive sheets, DP800 and AA6016, which are widely used in making car body parts. Uniaxial tensile and bulge tests are conducted to calibrate constitutive equations for modeling the tested materials. The developed material models are employed into different frameworks such as MMFC, MMFC2, and Marciniak-Kuczynski (MK) models to forecast the forming limit curve (FLC) of the tested materials. Their predictions are validated by comparing with an experimental one obtained from a series of Nakajima tests. It is found that the derived results of MMFC2 are comparable to that of MK model and agreed reasonably with experimental data. Less computational time is the major advantage of MMFC2 against the MK model.

Introduction

The formability of sheet metal is commonly evaluated by using a forming limit diagram (FLD). In this concept, a graphical representation of the forming limit, the forming limit curve (FLC), is used to separate the safe forming region in the strain space. Different testing setup, such as the Nakajima and Marciniak tests, can be used to determine the FLC experimentally [1]. In order to reduce the cost of experimental methods, huge efforts have been made to predict the FLC theoretically.

Publications of Swift [2] and Hill [3] are considered the pioneering works for this task. Storen and Rice [4] presented an alternative theoretical approach for FLC prediction. In this approach, the bifurcation analysis of deformation velocity was coupled with the deformation theory to determine the initiation of localized necking. Based on observations of geometrical imperfection of the tested coupon, Marciniak and Kuczynski [5] introduced a numerical procedure for predicting the FLC. Later, Hora et al. [6] formulated a criterion (MMFC) for neck determination based on the strain path change at the onset of diffuse neck.

Previous studies published in the literature demonstrate that these theoretical models may provide good predictions for FLC of some particular materials. Reviewing studies pointed out that there is not exist a universal model that can be applied for any metallic sheets. Recently, the MMFC is attractive because of its validation, which can be done with the use of digital cameras and correlation techniques (DIC). However, the application of the MMFC is limited due to some numerical issues, as discussed in references [7,8]. Recently, the authors discussed the reliability of theoretical assumptions implied in the MMFC, which leads to an improved version named MMFC2 [9].

This study presents comparisons between the applications of the original MMFC and the new version (MMFC2) for predicting the FLC of two automotive sheet metals, DP800 and AA6016. In addition, the predictions of MK model are also put into the comparison. Experimental FLC determined from the Nakajima tests are provided to discuss the reliability of these theoretical predictions.

The MMFC2 Model

Based on experimental observations of the strain path change beyond the diffuse neck, Hora et al. [6] introduced the condition for neck initiation as follows.

$$\frac{\partial \sigma_1}{\partial \varepsilon_1} + \frac{\partial \sigma_1}{\partial \beta}\frac{\partial \beta}{\partial \varepsilon_1} \geq \sigma_1 \tag{1}$$

In this equation, σ_1 and ε_1 denotes the principal major stress and the principal major strain, respectively; $\beta = \Delta\varepsilon_2/\Delta\varepsilon_1$ is the ratio between the minor and major strain increments. This equation results in an evolution of β, which is expressed as follows.

$$\Delta\beta = \frac{\sigma_1 - \frac{\partial \sigma_1}{\partial \varepsilon_1}}{\frac{\partial \sigma_1}{\partial \beta}}\Delta\varepsilon_1 \tag{2}$$

Hence, the strain localization is determined as soon as β approaches zero, indicating the plane-strain forming mode.

The condition is formulated based on the condition of maximum loading force observed during a uniaxial tensile test. In the MMFC, the strain path change is enforced to keep the maximum force unchanged. However, numerous experiments pointed out that the force drop may be up to 10% after the maximum for many automotive sheet metals [10]. Therefore, a scaling factor, ξ is proposed to slowdown the changing rate of β. Consequently, the evolution of β is updated as follows.

$$\Delta\beta = \xi\frac{\sigma_1 - \frac{\partial \sigma_1}{\partial \varepsilon_1}}{\frac{\partial \sigma_1}{\partial \beta}}\Delta\varepsilon_1 \tag{3}$$

In order to determine the value of ξ, a finite element simulation for uniaxial tensile test should be conducted to compare the simulated β evolution with the curve predicted by the MMFC for the uniaxial tension mode. In this study, a recommended value ($\xi = 0.5$) is adopted in the subsequent calculation without any further calibration.

For ductile materials, necking may occur before the fracture. Therefore, theoretical assumption of plane-strain forming mode at necking required in MMFC seems to overreach. An alternative condition for detecting the strain localization is presented as follows.

$$\left|\frac{d(\Delta\beta)}{d\underline{\varepsilon}}\right| \tag{4}$$

In other words, the localized neck is supposed to occur when the acceleration of strain path change reaches its minimum.

Calculation of the Forming Limit Curves

This study investigates two automotive sheet metals, i.e., DP800 and AA6016. The thickness of both materials is 1.2 mm. A series of Nakajima tests are conducted following the ISO 12004-2 standard to determine the experimental FLC for the examined materials. During these tests, the ARAMIS digital image correlation (DIC) system is used to monitor the strain field distribution on

the surface of the deformed specimens. The experimental FLC is calculated using the FLC built-in function in ARAMIS.

A proper material model is needed to calculate the theoretical FLC. For this purpose, constitutive models used to describe material's behavior under complex stress states were previously calibrated by Barlo et al. [11] and not be repeated here. The Swift hardening law [1] is adopted for DP800 whereas the Voce model [2] is applied for AA6016. Moreover, the Yld2000-2d yield function proposed by Barlat et al. [12] is applied to capture the yield surface of these tested materials. The formulations of these functions are expressed below.

$$\text{Swift}: H(\underline{\varepsilon}) = C(\varepsilon_0 + \underline{\varepsilon})^n \tag{5}$$

$$\text{Voce}: H(\underline{\varepsilon}) = S - a.exp(-b\underline{\varepsilon}) \tag{6}$$

$$\text{Yld2000-2d}: \underline{\sigma} = \left\{\frac{1}{2}\left(\left|X_1^{'} - X_2^{'}\right|^m + \left|2X_1^{''} + X_2^{''}\right|^m + \left|X_1^{''} + 2X_2^{''}\right|^m\right)\right\}^{1/m} \tag{7}$$

where C, ε_0, n, S, a, and b are hardening parameters; $X_{1,2}^{',''}$ are the principal values of two linearly transformed tensors which contain eight anisotropic parameters (α_1 – α_8) and the exponent parameter m. The calibrated parameters of each hardening law and yield function for the investigated materials are reported in Table 1 and Table 2, respectively.

Table 1. Hardening parameters of the tested materials.

Hardening law	Swift			Hardening law	Voce		
	C [MPa]	ε_0	n		S [MPa]	a [MPa]	b
DP800	1322.89	0.0012	0.165	AA6016	336.84	215.9	8.179

Table 2. Parameters of the Yld2000-2d function calibrated for the tested materials.

Yield function	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	m
DP800	0.9037	1.0270	1.0546	1.0055	1.0165	0.9367	0.9917	1.0306	6
AA6016	0.9633	0.9996	0.9438	1.0244	1.0134	0.9906	0.9683	1.1448	8

Fig. 1 depicts the calibrated hardening laws for both tested materials in comparison with the experimental data obtained from uniaxial tensile tests. Fig. 2 compares the predicted yield locus of these materials. These material models are employed in the framework of MMFC2 to predict their FLC. Moreover, the predictions of the original MMFC and MK models for the tested materials are also calculated for comparison purposes. A detailed description of these models can be found in Pham et al. [9].

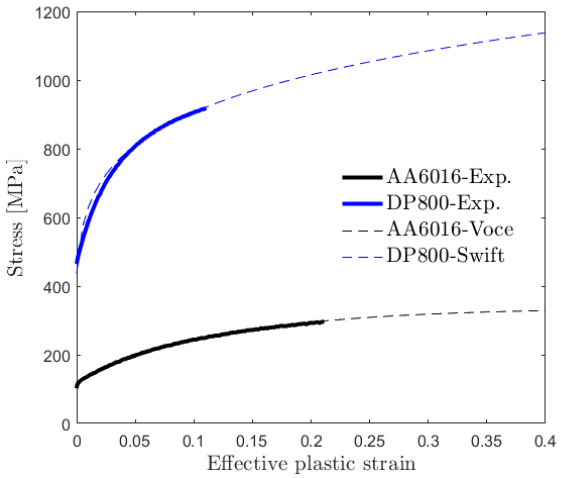

Fig. 1. Calibrated hardening law of the tested materials DP800 and AA6016.

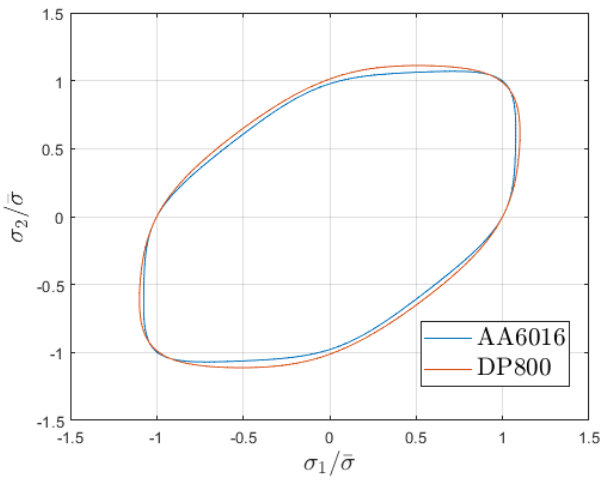

Fig. 2. Yield locus predicted by Yld2000-2d function for the tested materials.

Discussion

The predicted FLCs of DP800 and AA6016 sheets, based on different models, are compared with experimental data in Fig. 3 and Fig. 4, respectively. To simplify the comparison of the predicted and experimental FLCs, the experimental data were offset so the lowest forming limit point was moved to the plane strain region.

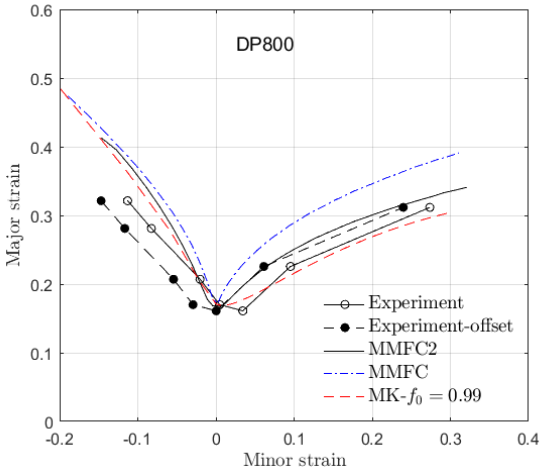

Fig. 3. Experimental and predicted FLCs of DP800.

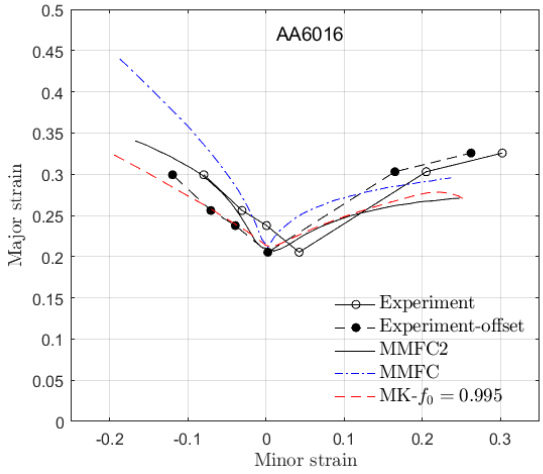

Fig. 4. Experimental and predicted FLCs of AA6016.

It can be seen in Fig. 3 that the MK model provides an excellent prediction of the experimental data of DP800, especially the region comprised between plane strain and biaxial tension. The MMFC model overestimates the experimental data, except for the plane strain point. Between uniaxial tension and plane strain regions, the MMFC2 agrees with MK model prediction, which is slightly higher than the experimental data. However, the results of MMFC2, in the right-side of the curve, lie in between these two other predictions.

In the case of AA6016 shown in Fig. 4, all theoretical models underestimate the experimental data in the biaxial tension regimes, probably due to the use of the Voce hardening law, which

shows a saturation stress in large strain ranges. In addition, the selected value of the exponent parameter, m influences the derived results, as discussed in [8]. Again, the MK model provides the best prediction for the left-side of the experimental curve. In contrast, the result of MMFC is significantly higher than the experiment. On the one hand, the MMFC2 presents an intermediate prediction for the left-side curve, whereas on the other hand, the result of this model for the right-side curve is close to that of the MK model.

The comparisons reveal that the prediction of the MK model is the most reliable among the considered theoretical models. The good performance of the MK model has been demonstrated in the literature for different materials subjected to different loading scenarios [13]. This study affirms the conclusion. The MMFC seems to overestimate the measured data of the tested materials. The MMFC2 improves the accuracy of the MMFC. Compared to the MK model, the MMFC2 derives comparable predictions for the FLC of the tested materials with an around five times faster computational time. The reason for the computational benefit of MMFC2 is due to its formulation, which does not require solving any system of non-linear equations as the MK model does. Details on the computational time of each theoretical model implemented in this study are reported in Table 3. According to this table, the computational efficiency of the MMFC2 seems negligible since the MK computational time is very good. However, the advantage gains more attractive when either a more complex material, such as, a distortional hardening model is adopted or a huge number of simulations is inquired, for example, in a data-driven application.

Table 3. Comparison between the computational time of theoretical models.

Theoretical model	MMFC	MMFC2	MK
Computational time (s)	20	25	120

Summary

This work aims to verify the potential of the newly proposed model MMFC2 for theoretically predicting the FLC of sheet metal. Two automotive sheets, DP800 and AA6016, were investigated by comparing the theoretical predictions of three different models, i.e., MMFC, MMFC2, and MK, with the experimental FLC obtained from Nakajima tests. The following conclusions can be made after this study.

- All theoretical models predict similar forming limits at the plane strain region, which are close to the experimental measurement.
- The MMFC model presents remarkably higher forming limits than the measured FLC.
- For both investigated materials, the predictions of the MMFC2 are comparable to those of MK model within a significant reduction of computational time.

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