LIMIT STRAINS VARIABILITY WITH RESPECT TO MATERIAL SCATTER

LIANA PĂRĂIANU, DAN SORIN COMSA, DOREL BANABIC

Abstract. In this paper a study regarding to the effect of the variability of the mechanical parameters on the prediction of the limit strain have been presented. The necking criterion used in the analyses is the one proposed by Marciniak-Kuczinsky [M-K]. The inelastic behaviour of the sheet metal has been described by BBC2005 yield criterion and Hill48 yield criterion respectively. The Swift's formulation has been used in order to describe the hardening of the material. The material investigated in this paper is DC04 steel sheet (0.85 mm thickness).

Key words: metal forming, failure, sheet metal.

1. INTRODUCTION

The automotive industry reported that a large number of rejected parts owe to the fact that the parameters of the sheet metal forming processes are not strictly constants. Col [1] emphasized the most important sources of scatter in a stamping process: material parameters, tooling, process and lubrication. During the last fifteen years, researchers paid attention to studying the variability of the mechanical parameters of both simulation plastic deformation processes and constitutive models.

The variability of the mechanical parameters cannot be neglected in a robust sheet metal forming process analysis. Gerlach *et al.* [2] is one of the first paper to do well on this issue. Karthik *et al.* [3] performed two kinds of tests on three types of steel in order to determine the variability of the mechanical parameters. These analyses emphasise the fact that the mechanical parameters are affected by the variability not only from lab-to-lab but also from coil-to-coil and test-to-test. More recently, after an in-depth study with conclusions published in [4–6], Carleer and his co-workers incorporated the variability of the mechanical parameters in the simulation of the sheet metal forming process. Since variability of the mechanical parameters became so important to virtual fabrication, AutoForm developed the Sigma module. The implementation of the stochastic modelling in the finite

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element program is presented in a subchapter of the book [7]. A strategy to deal with material properties variation in sheet metal forming has been developed by Atzema *et al*. [8, 9]. Rojek *et al*. [10] proposed a method to predict the sheet metal failure by typical deterministic and stochastic analysis. The variability of the mechanical parameters has been incorporate in models in order to evaluate the influence on the accuracy of the simulations: the risk of wrinkling and fracture [11], springback in the sheet stamping processes [12]. Recently, Aspenberg *et al*. [13] proposed a methodology for calibrating the material model in order to obtain the desired response of the sheet metal process.

The mechanical parameters influence the shape of the yield locus and the forming limit diagram (FLD) of the sheet metal. The variability of the Forming Limit Curves has been analyzed first time by van Minh, Sowerby and Duncan [14]. The concept of the forming limit band (FLB) has been introduced by Janssens *et al*. [15]. Strano and Colosimo [16] collected a large bibliography with experimental and theoretical FLDs for a specific material. There are some papers that study the FLB. Banabic and Vos [17] used the Marciniak-Kuczynski model to predict the FLB. Fyllingen *et al*. [18, 19] predicted the FLB using Monte Carlo Method (MCM) assuming a random thickness distribution. The method has been also proposed at the beginning of 90's by Narasimhan *et al*. [20] to predict the scatter band in forming limit strains. Kim et al. [21] used the diffuse necking criterion and the Monte Carlo simulation to predict the FLB for hydroforming process. Also, based on Marciniak-Kuczynski, Paraianu *et al*. [22] predicted the FLB using Monte Carlo Technique by taking into account the variability of the mechanical parameters. More recently, Paraianu [23] and Chiba [24] used the first-order reliability method in order to compute the forming limit band. An exhaustive study on optimization strategy applicable to forming processes liable to uncertainty has been presented by Wiebenga in his PhD Thesis [25].

The aim of this paper consists in achieving a study regarding to the influence of the mechanical parameters on predicted limit strains. The FLC has been obtained based on M-K [26] necking model, while the hardening follows the Swift's formulation. Two yield criteria have been involved in this study: the classical formulation of Hill48 yield criterion and BBC2005 yield criterion. Depending on the number of mechanical parameters of each constitutive law, the number of runs based on the Taguchi techniques has been established. The evaluation has been made with the help of ANOVA method.

2. NECKING CRITERION

The theoretical necking model used for calculating forming limit curve is based on Marciniak-Kuczinsky theory [26]. Figure 1 shows the schematic view of the limit strain M-K model. One may notice that the sheet metal forming with the nominal thickness (denoted as region A) is impregnate with a thinner strip (denoted as region B) [27].

In Fig. 1, the thickness from region A is denoted as ${}^{t}s^{(A)}$ while the thickness from the groove is denoted as ${}^{t}s^{(B)}$. The non-homogeneity factor (the variation of the sheet thickness) defined as the current ratio of the thicknesses is described by the quantity:

$$ {}^{t}f = {}^{t}s^{(B)} \big/ {}^{t}s^{(A)}, \quad 0 < {}^{t}f < 1 . \tag{1} $$

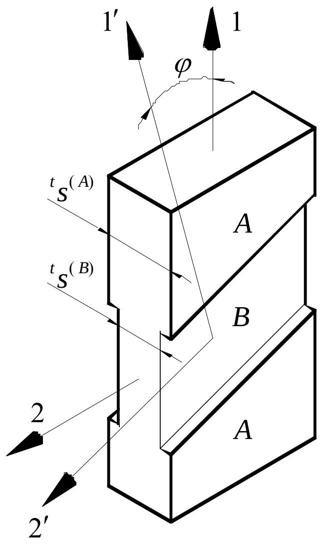

Fig. 1 – Marciniak-Kuczinsky model. Schematic view.

In our calculations, the initial value of the non-homogeneity factor is set to 0.999.

In order to calculate the right branch of the forming limit curve, the orientation of the strip is assumed to be perpendicular to the traction direction. In the case of the left branch of the FLC, the inclination of the necking band given by the angular parameter φ is

$$ \varphi = \arctan\sqrt{\max\left[-\rho^{(A)},0\right]}, \quad -1 < \rho^{(A)} \le 1 , \tag{2} $$

where $\rho^{(A)} = \dot{\varepsilon}_2^{(A)} \big/ \dot{\varepsilon}_1^{(A)} = \text{const.}$ is the strain-rate ratio associated to region A.

The implicit scheme allows the reduction of the M-K model to the numerical solution of a single non-linear equation. An exhaustive description of the mathematical approached you may find in [28].

As was mentioned above the sheet metal is supposed to behave as a rigid-plastic material and hardening follows the Swift formulation:

$$ Y = K\left(\varepsilon_0 + \overline{\varepsilon}\right)^n , \tag{3} $$

where *K*, *n* and ε_0 are mechanical parameters determined by fitting the results of tensile test.

3. EXPERIMENTAL FRAMEWORK

3.1. INVESTIGATED MATERIAL

The material investigated in this paper is DC04 quality steel sheet with 0.85 mm thickness. This material has been chosen for the study due to the fact that it is frequently used in the automotive industry. The chemical composition of the material is presented in Table 1.

Table 1

Chemical composition of the DC04 steel sheet

Carbon	Manganese	Phosphorus	Sulphur	Iron
0,08%	0,40%	max. 0,03%	max. 0,03%	Rest till 100%

3.2. DETERMINATION OF THE MECHANICAL PARAMETERS

The uniaxial mechanical parameters determined are yield stresses and Lankford coefficients. The samples have been cut at 0°, 45° and 90° from the rolling direction. The experiments have been performed on Zwick-Roell 150 kN tensile-compression testing machine equipped with an extensometer with 20 mm gauge-length. The only parameter from hardening law that has been taking into account in this study is the exponent coefficient of Swift's formula (n) and it was determined on samples cut at along rolling direction. In order to compute the mean value and the standard deviation for each mechanical uniaxial parameter more than 30 tests have been performed. In this analysis it has been assumed that the variability of the material properties obeys the Gauss normal distribution [15]. Table 2 lists the mean, minimum and maximum values of the mechanical parameters as well as some statistical parameters such as standard deviation and coefficient of variation.

Besides the uniaxial mechanical parameters, the influence of the equibiaxial yield stress upon forming limit curve has been taking into account. Its value results from a hydraulic bulge test. In this process the specimen has been deformed under the pressure of the oil.

Table 2

Statistical values of the uniaxial mechanical parameters of the DC04 steel sheet

Material parameter	Min. value	Max. value	Mean value	Standard deviation	Coefficient of variation
Y_0 [MPa]	190.56	198.98	195.96	2.086	0.010
r_0 [-]	1.72	2.20	1.92	0.110	0.057
Y_{45} [MPa]	207.06	215.35	210.97	2.401	0.011
r_{45} [-]	1.17	1.44	1.31	0.062	0.047
Y_{90} [MPa]	201.75	209.79	205.49	2.154	0.010
r_{90} [-]	2.00	2.65	2.22	0.145	0.065
n [-]	0.20	0.21	0.21	0.002	0.009

The bulge test has been performed on ERICHSEN 142–20 universal sheet metal testing machine (Fig. 2). One may assume that the specimen behaves as a membrane under the plane-stress conditions. Also, one may suppose that in the polar zone the specimen deforms uniformly in all direction and based on Laplace equations the equibiaxial yield stress-strain curve has been determined.

Fig. 2 – Experimental stand consisting in the ERICHSEN bulge test device and the ARAMIS 3D.

The calculations have been made with the help of 3D ARAMIS measurement system (Fig. 2). The methodology for determining the equibiaxial yield stress is detailed presented in [29]. Due to the fact that its determination is rather difficult, the standard deviation of these parameters has been set equal to the standard deviation of the yield stress determined along the rolling direction.

4. SENSITIVITY ANALYSIS OF THE LIMIT STRAINS

Taguchi method [30] has been applied in order to study the influence of the mechanical parameters on the limit strain. In this study eight mechanical parameters have been taking into account. For all these mechanical characteristics the standard deviation has been experimentally determined. Based on the assumption that the scatter of the mechanical parameters can be described by Gauss normal distribution two levels of their values have been calculated. Table 3 lists the values of the mechanical parameters for each level. The lower level was established by subtracting 3Sigma from the mean value, while the upper level results by adding 3Sigma to the mean value. Using this method the number of numerical simulations could be established. The method is able to catch the interaction effect between various controllable factors. In this study eight noise mechanical parameters have been studied in order to determine their influence on the predicted limit strains.

Table 3

Material characteristics and their two levels

Mechanical parameters	Level 1	Level 2
n_0	0.2037	0.216
Y_0 [MPa]	189.7	202.22
r_0	1.59	2.25
Y_{45} [MPa]	203.77	218.18
r_{45}	1.13	1.51
Y_{90} [MPa]	199.03	211.96
r_{90}	1.78	2.66
Y_b [MPa]	243.462	255.978

In the following, a comparative study of the influence of the mechanical parameters on forming limit curve based on two plastic constitutive models has been presented. Therefore, the plastic behaviour has been described by Hill48 yield criterion, BBC2005 yield criterion respectively. The identification procedure of classical Hill48 uses four mechanical parameters $\left(r_0, r_{45}, r_{90}, Y_0\right)$ while BBC2005 yield criterion uses seven mechanical characteristics $\left(r_0, r_{45}, r_{90}, Y_0, Y_{45}, Y_{90}, Y_b\right)$. In both cases, the hardening follows the Swift formulation and only the influence of exponent has been discuss.

In order to determine the influence of the mechanical parameters on the predictions of the limit strains, the simulations have been performed again according to L8 and L12. Tables 4 and 6 show the L8 and L12 orthogonal arrays used in order to perform the simulations. The responses of the model have been listed in the last three columns of the tables. The responses correspond to the equibiaxial, plane strain and uniaxial regions of the forming limit curve.

Tables 5 and 7 list the contribution (%) of each mechanical parameter on prediction of the limit strains (BT-biaxial traction, PS – plane strain condition and UT – uniaxial traction). The influence is given in percent. In the case of Hill48, the predictions of the limit strains in tension-tension region are more influenced by r_0 (about 66.7%) followed by r_{90} (about 32%).

Table 4

L8 orthogonal array and the model response
for three regions of limit strains for Hill48 yield criterion

No. of simulation	n_0	Y_0	r_0	r_{45}	r_{90}	BT	PS	UT
1	1	1	1	1	1	0.6467	0.176	0.467
2	1	1	1	2	2	0.5855	0.176	0.467
3	1	2	2	1	1	0.5585	0.176	0.588
4	1	2	2	2	2	0.4983	0.176	0.588
5	2	1	2	1	2	0.5088	0.188	0.626
6	2	1	2	2	1	0.5696	0.188	0.626
7	2	2	1	1	2	0.5961	0.188	0.497
8	2	2	1	2	1	0.6578	0.188	0.497

Table 5

Contributions (%) of the mechanical parameter on the limit strains
(biaxial, plane strain and uniaxial regions of the FLC)

Material parameter	BT%	PS%	UT%
n	1.012	99.8266	6.903
Y_0	– 0.001	– 0.0004	0.087
r_0	66.738	0.0913	93.01
r_{45}	– 0.0003	– 0.0006	0.000
r_{90}	32.2438	0.0789	0.000
Error - other parameters	0.0005	0.0001	0

Table 6

L12 orthogonal array and the model response for three regions of limit strains
in the case of the BBC2005 yield criterion.

No. of simulation	n	Y_0	r_0	Y_{45}	r_{45}	Y_{90}	r_{90}	Y_b	BT	PS	UT
1	1	1	1	1	1	1	1	1	0.309	0.174	0.465
2	1	1	1	1	1	2	2	2	0.307	0.174	0.465
3	1	1	2	2	2	1	1	1	0.340	0.174	0.586
4	1	2	1	2	2	1	2	2	0.332	0.174	0.465
5	1	2	2	1	2	2	1	2	0.354	0.174	0.586
6	1	2	2	2	1	2	2	2	0.434	0.174	0.586
7	2	1	2	2	1	1	2	1	0.312	0.186	0.626
8	2	1	2	1	2	2	2	1	0.415	0.186	0.626
9	2	1	1	2	2	2	1	2	0.307	0.186	0.497
10	2	2	2	1	1	1	1	2	0.321	0.186	0.626
11	2	2	1	2	1	2	1	1	0.386	0.186	0.497
12	2	2	1	1	2	1	2	1	0.397	0.186	0.497

Table 7

Contributions (%) of mechanical parameters on the limit strains

Material parameter	BT%	PS%	UT%
n	1.283	99.746	7.682
Y_0	19.809	0.0003	0.000
r_0	6.835	0.166	92.199
Y_{45}	-0.0528	0.0008	0.000
r_{45}	2.035	0.00003	0.000
Y_{90}	13.38	0.054	0.000
r_{90}	11.915	-0.0001	0.000
Y_b	43.911	0.030	0.000
Error -other parameters	0.8848	0.00297	0.119

As expected, n_0 is the only parameter that matters in the plane strain region. In the last region (tension-compression) only one parameter should been carefully taking into account (r_0 – about 93%).

In the case of BBC2005 yield criterion, the largest influence in the biaxial region is given by the biaxial yield stress (about 44%) followed by Y_0 (about 19%). The predicted limit strains in plane strain and tension-compression regions are influenced by the Swift hardening law exponent (about 99.8%) and r_0 (about 92%), respectively.

Figures 3 and 4 show the yield loci predicted by the Hill48 and BBC2005 yield criteria, respectively. The runs performed are according to the parameters obtained from the L8 and L12 orthogonal arrays. The scattering noticed on Figure 3 in the biaxial region is a consequence of the fact that the identification procedure of Hill48 yield criterion does not use the biaxial yield stress. In the case of the BBC2005 constitutive model the predictions are more grouped (as noticeable in Fig. 4).

Figures 5 and 6 show the forming limit curves obtained by varying the mechanical parameters if Hill48 and BBC2005 yield criteria are used. One may notice that in the left branch of the curve, the results are grouped. This is a consequence of the fact that one parameter has a very strong influence on the predictions of the limit strains (r_0 about 93% and 92%, respectively). The same grouped results have been obtained in the plane strain region where the parameter n has a larger influence on the predictions of the limit strains. The results are grouped around the levels of these parameters. But in the right branch of the FLC, a strong scattering of the responses can be observed. Even if the limit strains are larger if Hill48 is used, the width of the limit band is the same for both yield criteria.

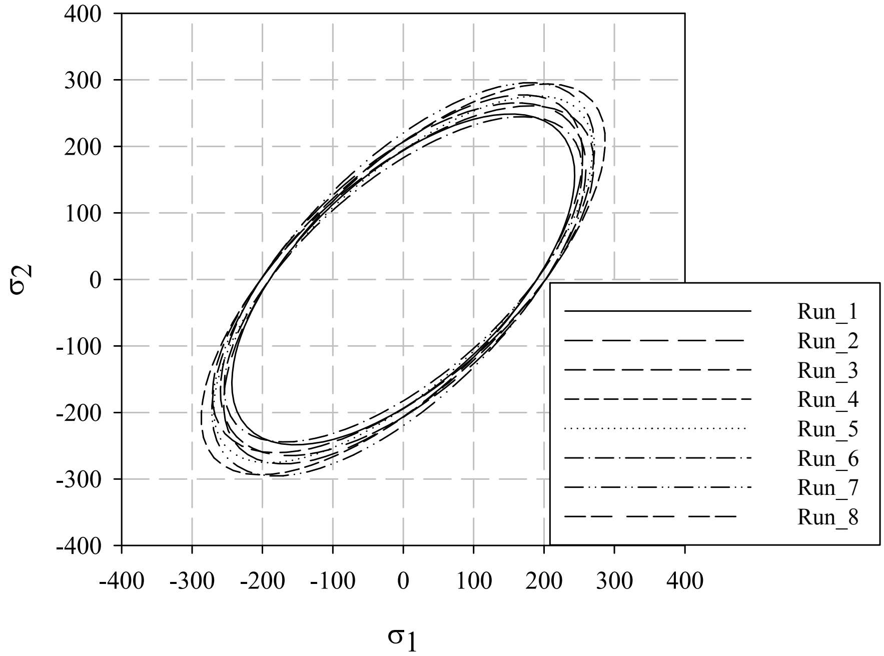

Fig. 3 – Yield loci predicted by Hill48 yield criterion obtained by varying the mechanical parameters.

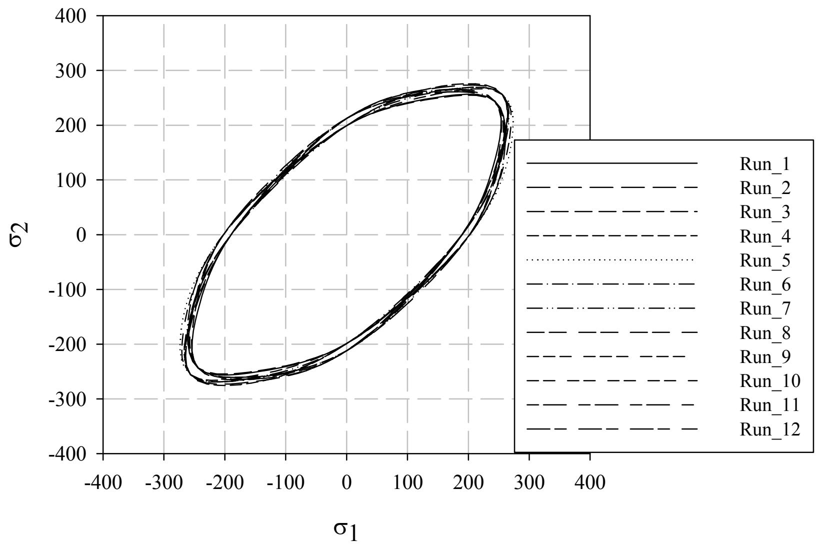

Fig. 4 – Yield loci predicted by BBC2005 yield criterion obtained by varying the mechanical parameters.

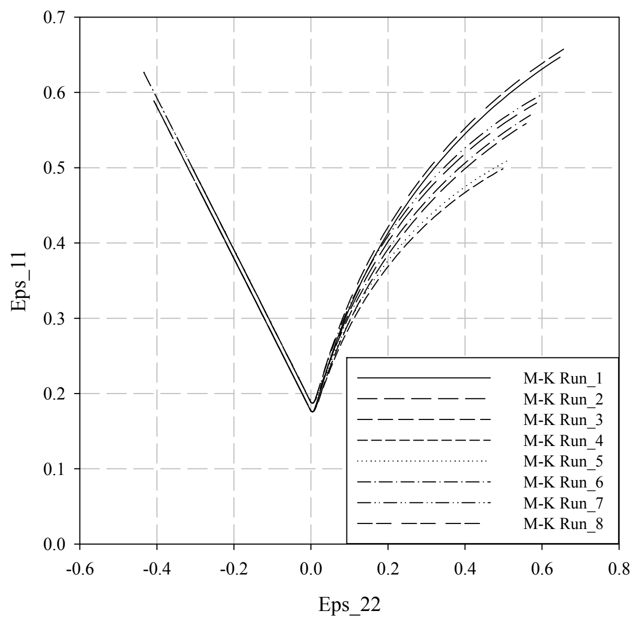

Fig. 5 – Forming limit curves obtained by varying the mechanical parameters for Hill48 yield criterion and M-K model.

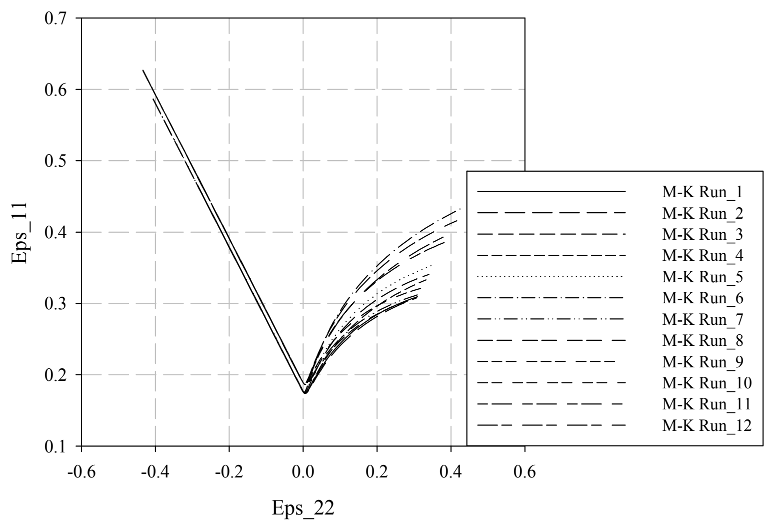

Fig. 6 – Forming limit curves obtained by varying the mechanical parameters for BBC2005 yield criterion and M-K model.

5. SUMMARY

The variability of mechanical parameters is a fact that cannot be neglected. In this study, the analyses of the influence of the variability of the mechanical characteristics on limit strains have been presented. The limit strain has been predicted by the M-K necking criterion. The predictions of two necking criteria and one hardening law have been taken into account. The mechanical behaviour of the steel sheet metal has been described using Hil48 and BBC2005 yield criteria, respectively. The number of mechanical parameters that have been taken into account depends on the constitutive models. In the case of Hill48, the influences of four mechanical parameters are discussed, while in case of BBC2005 seven mechanical parameters are involved in the study. The influence of the hardening exponent (n) on the limit strains has been analyzed in each case. The study has been possible with the help of Taguchi and ANOVA methodologies. From this analysis some interesting remarks could be established. As expected, in the plane strain area of the limit curve, the mechanical parameter n has the greatest influence on the predicted limit strain. In the equibiaxial region, if Hill48 yield criterion is used, the strongest influence on the predictions is given by r_0 (around 66%). The rest of the percent influence was covered by r_{90}. In the tension-compression region of the FLC, r_0 also has a stronger influence 93%. If the plasticity has been described by BBC2005 yield criterion, in plane strain region n has the greatest influence on the predictions of the limit strains. In the tension-tension region, Y_b has the most important influence. The following parameters in the descending importance of influence are: Y_0, Y_{90} and r_{90}.

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