

Variability analysis of the mechanical parameters in order to determine the Forming Limit Band

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Abstract. The variability of the so called noise factors greatly influences the results of any forming process (deep-drawing, stretching, etc.). By taking into account this variability, the number of the rejected parts and the manufacturing costs will decrease. The aim of this work is to evaluate the variability of the mechanical parameters of a DC04 steel sheet (0.85 mm thickness). The experimental data needed for evaluating the variability of the mechanical parameters has been obtained from uniaxial tensile tests. A total number of 113 experiments have been made using samples cut at 0°, 45° and 90° with respect to the rolling direction. In this way, the yield stress and the plastic anisotropy coefficient have been determined for each of the orientations mentioned above. The power hardening law offers the possibility to study the variability of the following parameters: yield stress, strength coefficient and strain-hardening exponent. Based on the dispersion of the stress-strain curves, the mechanical coefficients of the Swift hardening law have been determined using a new method. The input parameters exhibiting the most important influence on the scattering of the forming limit diagram have been also established. Finally, in order to determine the Forming Limit Band (FLB), a Monte-Carlo analysis (MCA) has been performed using values and correlations between the mechanical parameters.

Keywords: Forming Limit Band, variability of the mechanical parameters, Monte-Carlo analysis.

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INTRODUCTION

The correct description of the material behavior is very important for the sheet metal forming processes simulation. By having control on all the parameters involved in the process, the number of rejected parts is decreased. The results of the sheet metal forming processes depend on the input parameters which have scattered values and also suffer modifications during these processes. The following parameters are generally affected by the variability [1]: material parameters, tooling, process, and lubrication.

The material characteristics are important parameters involved in a mechanical process and have the most significant influence on the quality of the finished parts. These parameters have a probabilistic variance defined by a mean value, a standard deviation, and the coefficient of variation [2].

The process variable effects on the robustness of the sheet metal process were studied by Siekirk [3] and recently by Zhang and Shivpuri [4]. Gerlach and al [5] proposed a method to increase the robustness of the sheet metal forming process simulation despite of the variability of mechanical parameters of the sheet. Karthik et. al. [6] studied the variability of the mechanical parameters of three steel alloys. Two types of tests performed in two laboratories on 45 coils of materials led to the following conclusion: scattered values have been obtained from coil-to-coil but also to test-to-test or lab-to-lab. The relevance of the scatter of mechanical parameters for assessment of the formability of the sheet parts has been analyzed by Till and Rechberger [7]. Carleer and his coworkers published a series of papers [8], [9], [10] that present a methodology to establish a robust manufacturing process. In order to improve the prediction of the reliability of the production, Carleer incorporated the variability of the mechanical parameters in the simulation of the sheet metal forming process. A summary of his results is presented by Carleer in a subchapter in a recently book [11]. A strategy to deal with material properties variation in sheet metal forming has been developed by Atzema et al. [12], [13]. Rojek et al. [14] shows the possibility of sheet failure prediction by typical deterministic and stochastic analysis. Schleich et al. [15] studied the mechanical parameters of an AA6016 aluminum alloy. Some linear correlation functions between the parameters were found. Marretta and Di

Lorenzo [16] and de Souza and Rolfe [17] studied the influence of the material properties variability on springback in the sheet stamping processes.

The mechanical parameters influence 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 [18]. Analyzing a large set of experimental results they concluded that the scatter in measured forming limits is due, on the one side, to the errors in the experimental method and, on the other hand, to the scatter of the material properties. Janssens et.al. [19] presented an experimental study on the accuracy of the FLD determinations and introduced the concept of the Forming Limit Band (FLB). Strano and Colosimo [20] collected a large bibliography with experimental and theoretical FLDs for a specific material. These authors have noticed a large scattering of the data both in the case of experimental and theoretical FLD's. In general, the variability of the mechanical parameters leads to a lower and higher forming limit curve. Thereby, the concept of FLB has been introduced. In order to predict the FLB different approaches have been developed. Banabic and Vos [21] used the Marciniak–Kuczynski model to predict the FLB. They determine the lower and upper forming limit by taking into account the variation of the parameters of the yield locus and the hardening rule. Fyllingen et al. [22], [23] 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. [24] to predict the scatter band in forming limit strains. Kim et al. [25] used the diffuse necking criterion and the Monte Carlo simulation to predict the FLB for hydroforming process.

The main purpose of this work is to evaluate the variability of the mechanical parameters of a DC04 steel sheet. Some linear correlations between the mechanical parameters used in the FLD determination have been observed. The material parameters of the Swift hardening law have been determined with a new identification method. By introducing these relationships in a Monte Carlo Analysis, a FLB can be drawn.

EXPERIMENTAL FRAMEWORK

In this study, a DC04 steel sheet (0.85mm thickness) has been used. The chemical composition of this material is (according to EN 10130:2006 [26]): 0,08% Carbon, 0,40% Manganese, max 0,03% Phosphorus, max 0,03% Sulfur and rest up to 100% Iron.

In order to determine the variability of the mechanical parameters, 42 tensile tests have been performed using samples cut at 0° with respect to the rolling direction. Additionally, 33 tensile tests have been made using samples cut at 45° with respect to the rolling direction and 38 tensile tests using samples cut along the transverse direction. The literature [19], [21] specifies that a confidence level of 99.5% can be attained by performing at least 30 tests for each direction in the plane of the sheet metal.

The tests have been performed in order to determine the following mechanical parameters: yield stresses and anisotropic coefficients, as well as the n and K coefficients of the Hollomon hardening law. The following statistical parameters have been calculated for these quantities: mean or expected value of the noise variables (x) that describe the central location of the data; standard deviation shows the variation or "dispersion" of the experimental data from the "average" (mean or expected) value. A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data is spread out over a large range of values; Coefficient of variation is defined as the ratio of the standard deviation (σ) to the mean (\bar{x}). This quantity is only defined for a non-zero mean, and is most useful for variables that are always positive. It is sometimes expressed as a percentage, so that the value here should be multiplied by 100.

In order to build a reliable and robust FLB a correlation between mechanical parameters must be established. Table 1 shows the characteristic values of the mechanical parameters obtained from experiments, together with their

TABLE1. Mechanical parameters of the DC04 steel sheet (0.85 mm thickness)

Material parameter	Minimum value	Maximum value	Mean value	Standard deviation	Coefficient of variation
Y_0	190.56	198.98	195.96	2.086	0.010
r_0	1.72	2.20	1.92	0.110	0.057
n_0	0.20	0.21	0.21	0.002	0.009
Rm_0	303.39	312.51	308.75	2.025	0.006
K_0	519.40	531.88	526.97	3.800	0.011
Y_{45}	207.06	215.35	210.97	2.401	0.011
r_{45}	1.17	1.44	1.31	0.062	0.047
Y_{90}	201.75	209.79	205.49	2.154	0.010
r_{90}	2.00	2.65	2.22	0.145	0.065

minimum and maximum values. The statistical coefficients mentioned above have been calculated for each parameter.

As one may notice, the coefficients of plastic anisotropy have the most important variation, namely 28% at 0°, 44% at 45° and 32.5% at 90°. The smallest range of variability corresponds to the yield stresses: 4.4%, 4% and 4% for 0°, 45° and 90°, respectively.

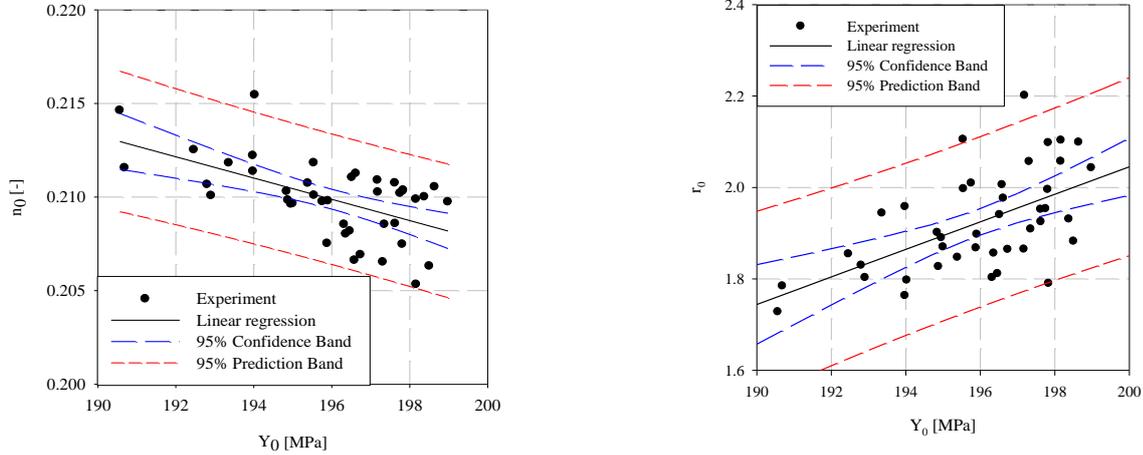


FIGURE 1. Relationships between mechanical parameters determined at 0° from the rolling direction: a) correlation between the yield stress and the hardening exponent of Hollomon's law; b) correlation between yield stress and the anisotropy coefficient

Figure 1 shows the uniaxial yield stresses and the corresponding values of the hardening exponent and plastic anisotropy coefficient. The experimental points in the diagram have been obtained from tensile tests performed along the rolling direction. As noticeable in Figure 1, a linear correlation between the mechanical parameters can be determined. This correlation is shown on the diagram together with the confidence and prediction band corresponding to an accuracy level of 95%. The linear correlation functions of the mechanical parameters have the following expressions:

$$\begin{aligned}
 n_0 &= 0.3212 - 0.0006 Y_0 \\
 K_0 &= 343.9275 + 0.9341 Y_0 \\
 r_0 &= -3.9824 + 0.0301 Y_0 \\
 r_{45} &= 1.68 - 0.0017 Y_{45} \\
 r_{90} &= 1.1505 + 0.0052 Y_{90}
 \end{aligned}
 \tag{1}$$

The set of expressions (1) has been used in the prediction of the upper and lower forming limits curves by using the Marciniak-Kuczynski model.

DETERMINATION OF SWIFT'S HARDENING LAW TACKING INTO ACCOUNT THE VARIABILITY OF THE MECHANICAL PARAMETERS

Based on the dispersion of the stress-strain curves, the mechanical coefficients of the Swift hardening law have been determined using a new method. This method is presented in the following.

The mathematical formulation of Swift's hardening law is

$$Y(\varepsilon) = K(a + \varepsilon)^n
 \tag{2}$$

where Y is the yield parameter, ε is the accumulated plastic strain, while K , a and n are material parameters obtained from an identification procedure.

Let $\varepsilon_i, i = 1, \dots, N$, be a set of discrete values obtained by equal partitioning the range of plastic strains associated to the tensile tests performed along the rolling direction. Each of the discrete values $\varepsilon_i, i = 1, \dots, N$, can be put into correspondence with an average yield stress Y_i and a standard deviation σ_i representing the spread of the experimental yield stresses around the average value Y_i . The standard deviation can be used to define a weighing factor:

$$w_i = \frac{1}{\sigma_i^2} \quad (3)$$

In order to enhance robustness of the identification procedure, the Swift hardening law will be expressed in a logarithmic form:

$$\ln Y = K' + n \ln(a + \varepsilon), \varepsilon \geq 0 \quad (4)$$

where $K' = \ln K$.

The identification procedure is based on the least square method. More precisely, the procedure enforces the minimization of the following error-function:

$$f(K', a, n) = \frac{1}{2} \sum_{i=1}^N \left[K' + n \ln(a + \varepsilon_i) - \ln Y_i \right]^2 w_i \quad (5)$$

By taking into account Eqs (3) and (5), this function can be written as

$$f(K', a, n) = \frac{1}{2} \sum_{i=1}^N \left[\frac{K' + n \ln(a + \varepsilon_i) - \ln Y_i}{w_i} \right]^2 \quad (6)$$

The minimum conditions of the function f are

$$\frac{\partial f}{\partial K'} = 0, \quad \frac{\partial f}{\partial a} = 0, \quad \frac{\partial f}{\partial n} = 0 \quad (7)$$

These constraints are equivalent with the following set of equations:

$$\begin{aligned} K' \sum_{i=1}^N \frac{1}{\sigma_i^2} + n \sum_{i=1}^N \frac{\ln(a + \varepsilon_i)}{\sigma_i^2} &= \sum_{i=1}^N \frac{\ln Y_i}{\sigma_i^2} + n \\ K' \sum_{i=1}^N \frac{1}{(a + \varepsilon_i) \sigma_i^2} + n \sum_{i=1}^N \frac{\ln(a + \varepsilon_i)}{(a + \varepsilon_i) \sigma_i^2} &= \sum_{i=1}^N \frac{\ln Y_i}{(a + \varepsilon_i) \sigma_i^2} \\ K' \sum_{i=1}^N \frac{\ln(a + \varepsilon_i)}{\sigma_i^2} + n \sum_{i=1}^N \left[\frac{\ln(a + \varepsilon_i)}{\sigma_i^2} \right]^2 &= \sum_{i=1}^N \frac{\ln Y_i \ln(a + \varepsilon_i)}{\sigma_i^2} \end{aligned} \quad (8)$$

One may notice that Eqs (8) are linear with respect to the unknowns K' and n . As a consequence, any two of these equations can be easily solved with respect to these quantities. Of course, the solution will contain the coefficient a as a parameter. By replacing K' and n obtained from the solution procedure described above in the third of Eqs (8), one gets a non-linear equation containing only the parameter a as unknown. This equation can be solved only in a numerical manner (for example, by using the bisection method in combination with a bracketing procedure). As

soon as the parameter a is known, K' and n result from Eqs (8). In the last stage of the identification procedure, the original parameter K results from Eq (4).

Using this procedure, the following values of the coefficients of Swifts hardening law have been determined: $a = 0.01016$, $K = 547.314 \text{ MPa}$, $n = 0.238$. These values correspond to the set of 42 tensile tests performed along the rolling direction.

PREDICTION OF THE FLB USING THE MONTE CARLO ANALYSIS

As mentioned by Schleich et.al. [13], by taking into account the existing correlations between the mechanical parameters (see Eqs (1)), a FLB can be calculated. The yield stresses associated to the 0° , 45° and 90° directions have been chosen as independent parameters. Assuming a statistic distribution of these quantities, their values have been randomly generated in a $\pm 3\sigma$ range around the experimental average. By using Eqs (1), the following mechanical parameters have been calculated: r_0 , r_{45} , r_{90} , n and K . The BBC2005 yield criterion [27] has been used to describe the mechanical behavior of the sheet metal. The coefficients of the yield criterion have been determined using Y_0 , Y_{45} , Y_{90} , r_0 , r_{45} , and r_{90} as input data.

In order to determine the FLB, a Marciniak-Kuczynski [28] strain localization model has been applied. The inhomogeneity factor has been also randomly chosen between 0.990 and 0.999. Figure 2 shows the FLB calculated using MCA.

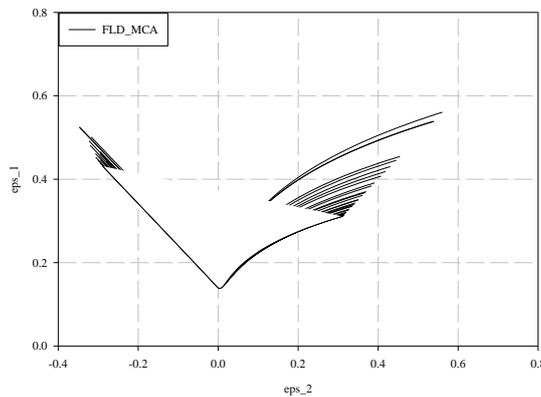


FIGURE 2. Forming limit band obtained using a Monte Carlo Analysis.

CONCLUSIONS

The paper presents a methodology for the calculation of the FLB that takes into account the variability of the mechanical parameters. The input parameters and their variability have been determined by performing 42, 33 and 38 tensile tests at 0° , 45° and 90° with respect to the rolling direction. The analysis of the experimental data shows that the coefficients of plastic anisotropy have the most important variation (28%, 44%, and 32.5% respectively). In contrast, the uniaxial yield stresses have a narrower variation range (about 4% in all cases). Using the results of the tensile tests, correlation linear functions of the mechanical parameters have been established. In order to determine the coefficients of the Swift hardening law, a new identification procedure has been proposed. The results provided by this procedure seem to be more realistic than the values measured by the tensile testing machine for individual specimens.

In the final section of the paper, a FLB has been calculated. Using the experimental data and the correlation functions, a Monte Carlo scheme has been applied. The paper shows that a FLB can be obtained taking into account the variability of the mechanical parameters and the correlation functions between these quantities.

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