Influence of Variability of Mechanical Data on Forming Limits Curves

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The paper presents a quantitative analysis referring to the variability of the uniaxial and biaxial parameters describing the plastic anisotropy and hardening of the DC01 steel sheets and the influence of this variability on the results of the simulation of the sheet metal processes and on the prediction of the Forming Limit Curves (FLCs). The experimental data is acquired by means of tensile tests performed along three directions in the plane of the sheet metals, using flat specimens cut from two batches. The Nakazima test has been used to determine the Forming Limit Curves. The predicted FLCs are in good agreement with the experimental ones.

Keywords: Forming Limit Curves, Mechanical data, Sheet metal, Steel

Introduction

The application of simulation models in sheet metal forming, especially in the automotive industry, has proven to be beneficial to reduce tool costs in the designing stage and for optimising the manufacturing processes. Moreover, with a view to environmental, economic and safety concerns, the car manufacturers need to design lighter and safer vehicles in ever shorter development times. This means that the components have to be designed more critically regarding their forming and crash behaviour. This in turn means that the material models used in forming and crash simulations need to have a higher accuracy. In order to obtain a higher accuracy, the material models need to be improved as need the mechanical tests used to characterise the plastic behaviour of materials.

The results from the mechanical tests are necessary to determine the parameters of the material models used in the numerical simulation of the forming processes. Due to the manufacturing conditions (metal casting, rolling and heat treatment), the mechanical characteristics of the sheet metals are not rigorously constant. As a consequence, the result of the forming operations is not completely predictable by numerical simulation. In general, the differences between predictions and reality are due to the fact that the constitutive models use average values of the mechanical parameters. Knowing the variability of these material characteristics would allow performing numerical simulations not only for the average values, but also for the extreme ones. In this way, better predictions of the results obtained in real manufacturing processes become possible.

The Forming Limit Curve (FLC) represents an efficient tool to characterize the formability of sheet metals. FLC is a curve relating pairs of principal limit strains, which can be obtained at the surface of the sheet metal during a forming process prior to the occurrence of some defects. During the last 50 years, the concept of Forming Limit Diagram (FLD) introduced by Keeler and Backofen [1] and Goodwin [2], respectively, has had a remarkable impact on the academic and industrial communities. The importance of the concept consists in the possibility to establish the maximum strains that can occur before necking in a forming process.

The first theoretical FLC models were based on the diffuse necking and localized necking theories proposed by Swift [3], and Hill [4], respectively. In the seventh decade of the previous century, Marciniak and Kuczynski [5] proposed a theoretical model of strain localization based on the geometrical non-homogeneity already existing in the material. Later on, the Marciniak– Kuczynski model has been extended by Hutchinson and Neale [6] in order to describe the left branch of the FLC. An exhaustive description of the experimental and theoretical methods used for the determination of the forming limits can be found in [7] and [8].

We notice that the aim of obtaining a full robustness imposes a better evaluation of the uncertainly strip affecting the position of the FLC. Taking into account this fact, several researchers [9] and [10] have proposed a more general concept, namely the Forming Limit Band (FLB) as a region covering the entire dispersion of the FLCs. The authors have established an original method for predicting the two margins of the limit band [11]. A good agreement with the experiments has been obtained. However, some deviations could be noticed, especially in the left side of the diagram.

Experimental Determination of Mechanical Parameters Describing Plastic Behaviour

A DC01 steel grade of 1.0 mm thickness was used in the tests. DC01 is low-carbon steel suitable for operations inducing small or medium-level strains. At present, DC01 sheet metals are currently used for producing various components of the vehicles, heat exchangers, etc.

In order to establish the mechanical parameters of the DC01 steel sheets, uniaxial tensile tests have been performed. As the main objective of the investigation consisted in analysing the variability of the material characteristics, the specimens have been cut from different sheet areas, as well as from two different sheet metal batches. For each batch have been used 20 specimens for determination of each mechanical parameter.

The uniaxial tensile experiments have been performed using a Zwick-Roell Z150 testing machine controlled by the testeXpert II software. In order to establish a more comprehensive set of mechanical parameters, the flat specimens have been cut at 0º, 45º and 90º with respect to the rolling direction. The following characteristics have been determined: conventional yield stress $Rp_{0.2}$; coefficient of plastic anisotropy r; work-hardening coefficient K; work-hardening exponent n.

The identification procedures of many yield criteria used in the numerical simulation of the sheet metal forming processes use the yield stresses and coefficients of plastic anisotropy corresponding to the directions defined by 0º, 45º and 90º angles measured from the rolling direction. As concerns the work-hardening parameters, they are used for calibrating the empirical laws describing the evolution of the yield surface during the forming processes.

Figures 1 show the characteristic curves (true stress vs. true strain) resulted from the tensile tests performed on the specimens cut from the first batch of sheet metals.

Similar results have been obtained for the second batch. The corresponding values of the mechanical parameters $Rp_{0.2}$, r, K and n are listed for the both batches in **Table 1**.

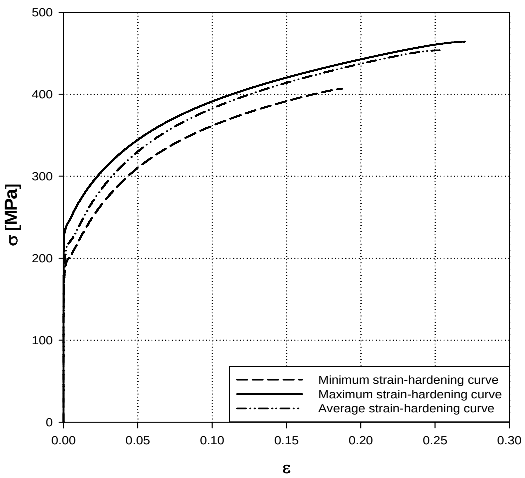

Figure 1. Strain hardening curves corresponding to specimens from the first batch cut at 0º with respect to rolling direction.

Table 1. Variability of conventional yield stress and coefficient of plastic anisotropy for batch 1(B1) and batch 2 (B2) of DC01 steel grade.

Angle	Val	Rp_{02} [MPa]		r		K [MPa]		n	
		B1	B2	B1	B2	B1	B2	B1	B2
0º	Min	201.0	194.8	1.339	1.703	585.0	585.5	0.198	0.199
	Ave	211.6	205.0	1.410	1.793	615.8	616.3	0.209	0.210
	Max	222.1	215.3	1.481	1.883	646.6	647.1	0.219	0.220
45º	Min	211.8	198.6	1.108	1.325	602.0	601.9	0.203	0.203
	Ave	223.0	209.1	1.166	1.395	633.6	633.6	0.214	0.214
	Max	234.1	219.5	1.224	1.465	665.3	665.3	0.225	0.225
90º	Min	205.8	194.9	1.821	1.913	576.7	577.5	0.185	0.198
	Ave	216.7	205.2	1.917	2.014	607.0	607.9	0.205	0.209
	Max	227.5	215.4	2.013	2.115	637.4	638.3	0.215	0.219

Influence of Variability of Mechanical Parameters on Predictions of Constitutive Models

The variability of the mechanical parameters has to be taken into account when performing numerical simulations. Any changes of these quantities affect the plastic behaviour defined by the constitutive model. The diagram presented in **Figure 2** is illustrative from this point of view. They prove the strong influence of the uniaxial yield stresses and anisotropy coefficients upon the yield locus, as well as on the planar distribution of the yield stress and r-coefficients in the case of the BBC 2005 constitutive model [12]. Similar diagrams can be obtained for other types of constitutive models [7].

Figure 3 presents an example of how the uniaxial yield stress in the rolling direction influences the thickness pre diction for a deep drawing cup simulation.

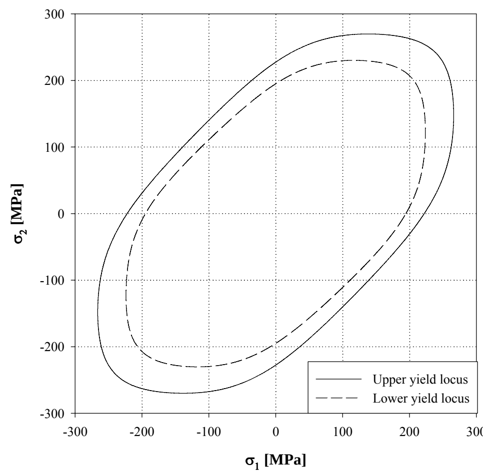

Figure 2. Upper and lower yield loci predicted by BBC 2005 model assuming variability of mechanical data of DC01 steel grade.

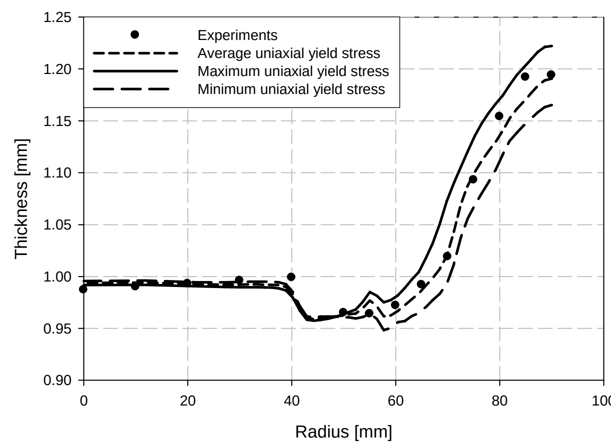

Figure 3. Influence of uniaxial yield stress in rolling direction on prediction of thickness in a cup drawing test.

Similar results have been obtained assuming the anisotropy coefficients variation and the biaxial yield stress. The influence of constitutive equations on the accuracy of prediction in sheet metal forming simulation is presented in the paper [13]. The results of the predictions are very sensitive to details in the material modelling, especially to the biaxial yield stress value.

Experimental Determination of Forming Limit Curves

One of the widely used methods to determine de FLCs is the Nakazima test [14]. This procedure consists in drawing the sheet specimens over a hemispherical punch (punch radius 40 mm) . The generic shape of the specimens used in the experiments is presented in **Figure 4**.

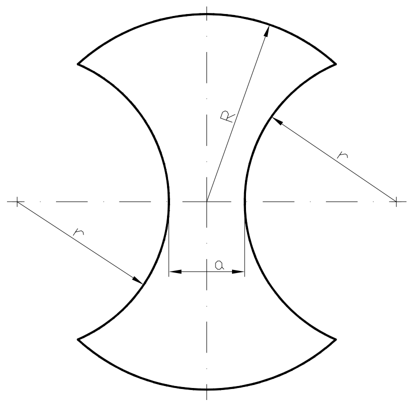

Figure 4. Generic shape of sheet specimens used in Nakazima tests.

In order to cover a wider domain of the limit strains, the radius r has been varied as shown in **Table 2**. Even in case of a very good lubrication, it is impossible to completely remove the frictional interactions between the specimen and punch.

Table 2. Dimensions of sheet specimens used in Nakazima tests (see also Figure 4).

R [mm]	r [mm]	a [mm]
75	60	30
75	54	42
75	43	64
75	0	150

Therefore, the Nakazima test cannot reach the equibiaxial limit strains ($\varepsilon 1 = \varepsilon 2$). Hydraulic bulging is the simplest procedure that can be used to obtain such a state. As one may notice, in this case, the punch is replaced by a hydraulic medium. The deformation of the sheet specimen is the result of the pressure applied on the bottom face.

The limit strains of the specimens subjected to punch stretching and hydraulic bulging have been measured with an Aramis system (**Figure 5**).

This device combines the advantages of photogrammetry with the advantages of the object grating method. The preparation of the specimen and the whole evaluation process for the determination of FLCs can be shortened and the overall costs of the material testing can be reduced significantly. Photogrammetry is one of the optical methods which lead to the 3D-coordinates of surface points. From this data, one gets the displacement vectors,

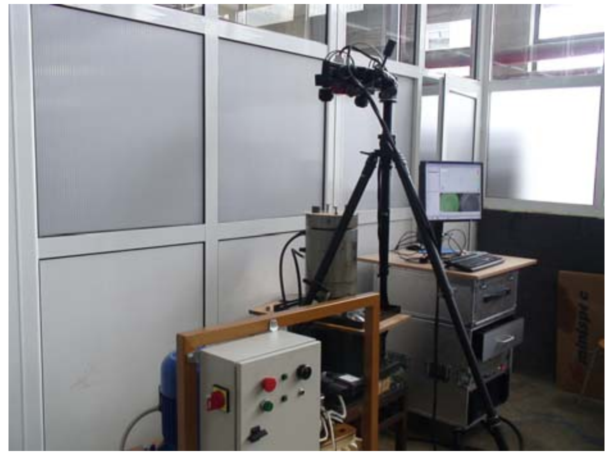

Figure 5. Experimental equipment for FLC determination.

the local strain values, and the contour difference, if the object is deformed. When the object points on the surface of the specimen are arranged like a grating, this is the technique well-known in experimental mechanics as the grating method. Instead of an expendable line mesh, a stochastic pattern is applied to the surface of the specimen using a graphite spray that allows a very high local resolution. Due to appropriate calculation methods, the resolution can be increased to sub-pixel range. The results (major and minor strains) can be presented in a graphical manner. For the determination of FLCs, sections through these graphs are taken in the necking/fracture zone. According to Bragard's method [8], a smooth parabola is used for the evaluation of the FLC [15].

Figure 6 show the Forming Limit Diagram determined by testing first batch of DC01 sheet metals. As one may notice, the experimental results are not rigorously coincident for the tested batches. This situation is a consequence of the variability that affects the mechanical parameters of the sheet metals subjected to the tests. In fact, the differences noticeable when comparing the limit strains presented in the Figure 6 suggest that sheet metals should be characterized by a Forming Limit Band (FLB) instead of a FLC. The FLB width is a statistical measure of the dispersion affecting the limit strains [11].

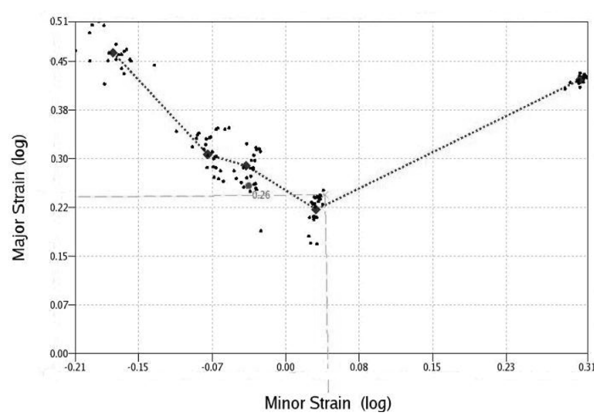

Figure 6. Experimental Forming Limit Diagram determined for first batch of DC01.

Prediction of Forming Limit Curves. Comparison with Experimental Data

The FLCs of the DC01 sheet metal has been predicted using the FORM-CERT computer programme developed in the frame of the CERTETA research centre [16]. The programme implements a computational scheme based on the Hutchinson-Neale model. In this approach, the main cause of the necking and fracture is a thickness defect. The amplitude of the defect increases during the deformation process until reaching the limit state when all the strain is concentrated in a small band. This stage corresponds to the occurrence of the necking.

In order to calculate the FLCs of the DC01 steel sheet, two sets of mechanical parameters of this material have been used. They are listed in Table 1 and correspond to the minimum and maximum values obtained from tensile tests.

The set of minimum values defines the lower boundary of the forming band, while the maximum ones will generate the upper bound. **Figure 7** shows the results obtained this approach. The experimental points collected from both batches are placed on the same diagram (Experiments_B1 and Experiments_B2, respectively). As one may notice, the FLB closely follows the distribution of the experimental points. This is a validation of the procedure used for determination of the FLB of the DC01 sheet metal and also of the computational algorithm implemented in the FORM-CERT programme.

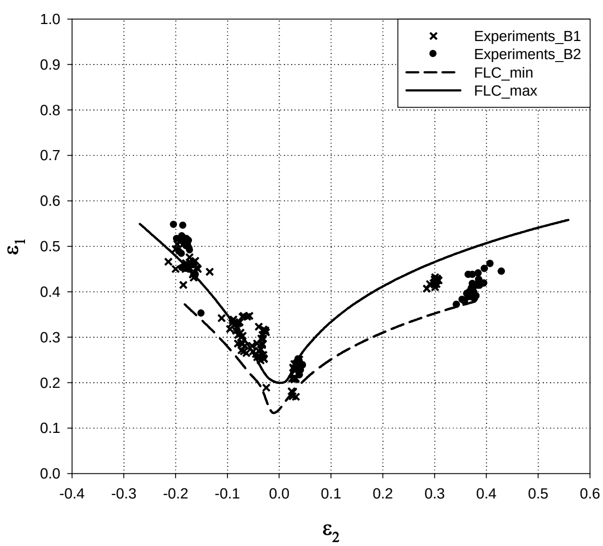

Figure 6. Predicted and experimental Forming Limit Band of DC01 steel sheets.

Conclusions

The research performed by the authors has been focused on analysing the variability of the mechanical parameters used to describe the plastic behaviour of sheet metals. The experimental results obtained in the case of the DC01 steel grade show notable dispersions of the material characteristics. The authors also prove that the variability of the mechanical parameters has a strong influence on the plastic behaviour predicted by the constitutive models. The influence of the variability of the uniaxial yield stress on the accuracy of prediction in deep drawing simulation is also presented. The formability of the DC01 steel sheets has also been investigated both by experiments and numerical calculations. The results obtained from Nakazima and hydraulic bulging tests show a dispersion of the limit strains. This fact suggests that sheet metals should be characterized by a FLB rather than a FLC. The Hutchinson-Neale model is able to predict the FLB if the variability affecting the mechanical parameters of the sheet metals is taken into account. Almost of the experimental points representing the limit strains take values between the FLC_min and FLC_max, the bounds of the FLB. The results presented in the paper are useful for increasing the robustness of the sheet metal forming simulation and thus reducing the risk of defects.

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