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Numerical determination of the forming limit diagrams

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Analysis and modelling

ABSTRACT

Purpose: At present the industrial practice demands a reliable determination of forming limits which assures the prediction of properly selecting the forming process in a digital environment. Therefore, technological limits defined with the forming limit diagrams (FLDs) have to be known. The experimental evaluation of FLDs for sheet metal is time consuming and demands expensive equipment. The experimental work could be omitted by predicting the FLD with numerical simulations.
Design/methodology/approach: The paper presents a methodology to determine the entire range of the FLD for sheet metal in a digital environment. The Marciniak testing procedure simulated with the FEM program ABAQUS was selected to determine the FLD. To assure the reliability of the developed method, different materials were analysed: two types of deep drawing steel, an aluminium 3000 alloy, and a Ti-alloy. The selected materials have different mechanical properties and sheet thicknesses ranging from 0.5 mm to 1.23 mm. For the verification of numerically obtained results parallel experimental determinations of the FLDs were performed showing a good correlation between the FLDs obtained by both approaches.
Findings: A specially developed method for the evaluation of the thickness strain as a function of time as well as the first and the second time derivation of the thickness strain enable the determination of the onset of necking.
Research limitations/implications: The presented method of the digital evaluation of the FLDs is still in a developmental phase and needs further improvements for industrial practice. However, in some cases the numerical approach had already been used for a fast prediction of the FLD prior to performing the experiments. At the current level the developed program still needs an expert to support it in some critical decisions.
Originality/value: Considering some methodological improvements and automation procedures the developed method could be used in everyday practice.
Keywords: Numerical techniques; Plastic forming; Sheet metal; Forming limit diagram

1. Introduction

The processing of sheet metal is affected by numerous parameters, such as material behaviour, tooling, lubrication, necessary machinery, etc. All mentioned parameters have an influence on technological limitations of sheet metal forming, its wrinkling, necking and rupture. The last two are among the most critical defects appearing in sheet metal fabrication.

One of the most important input parameters for the numerical simulations of the forming process in a digital environment represents accurate material data of formed sheet metal. There are several data describing the material behaviour of sheet metal, such as its flow curve, coefficients of normal and planar anisotropy, yield stress and the formability limits, respectively.

2. Forming limit diagram

The development of the production of new parts, its set-up of forming an operation or several progressive operations demands good knowledge of the attainable forming limits. It is necessary to define the limit up to which the material can be formed. Above this limit the localisation with necking and fracture appears. Nowadays it is particularly impossible to perform the analyses of the forming process in a digital environment when fracture data are not known as an input parameter.

The idea of a sheet metal evaluation with a diagram consisting of the first main strain versus the second one which was named the forming limit diagram (FLD) was introduced in the late 1960s by Keeler and Goodwin [1]. With this so-called forming limit diagram it is possible to evaluate different strain conditions in the same diagram and determine its fracture limits for a particular strain combination – Fig. 1.

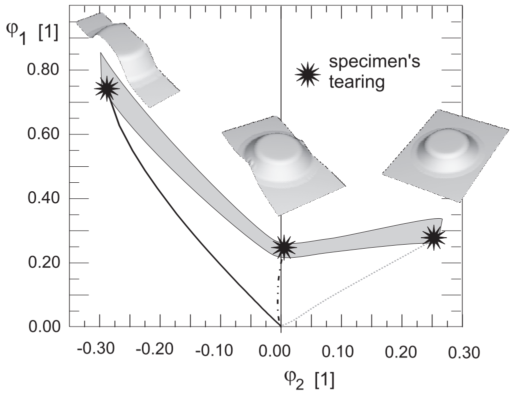

Fig. 1. Forming limit diagram

The first pioneer works of the experimental determination of the FLD by Keeler and Goodwin were followed by numerous research activities ranging from the improved methods for experimental determination of the FLD to analytical concepts allowing the calculation of the FLD up to numerical approaches which are based on the simulations of various testing methods in a digital environment.

Among several developed experimental tests two of them have shown exceptional suitability for the evaluation of the entire range of the FLD combined with simple tooling and an experimental procedure – these are the Nakazima and the Marciniak test. A Polish scientist Marciniak introduced a method for the determination of the FLD with a flat punch [1]. The test tool consists of the drawing die, the blankholder and the punch. The punch has an even and a partially sunk forehead. Various strain conditions are achieved by different widths of the analysed specimens which enable the determination of the entire range of the FLD with one tool geometry only. During the testing procedure the even punch forehead causes the plane strain conditions in the analysed specimen area.

Parallel to the experimental approach a computer-aided numerical approach in a digital environment was sought and introduced in the last years. The finite element method, commonly used for the numerical solving of forming processes with the FLD as an input parameter, was selected to analyse the Nakazima and Marciniak testing procedure. Comparative studies were done in the area of numerical determination of the forming limit curve (FLC) where different criteria of necking and fracture were presented. One of the first in this research area was Brun [2] analysing the material's thinning in order to determine the onset of necking by the Nakazima method. The method is applicable to the entire range of deformation states of the FLD.

Unfortunately, the evaluation of various materials showed that the leaping change of thinning acceleration (second thinning derivation in time) is not at all times significant to the point that the determination of the necking point could be doubtlessly determined. This is the case at the right hand side of the FLD with $\varphi_2>0$ in particular as well as with some materials on the entire range of the FLD. Therefore, the research was focused on the criterion which would allow a simple and reliable determination of the necking limit.

3. Numerical and experimental analyses of forming limit diagrams

3.1. Methodology for temporal and spatial determination of material necking by the Marciniak test

Based on Brun's idea, the presented paper introduces the methodology of spatial and temporal identification of the necking of critical nodes of the FEM model and the determination of their corresponding strains φ_1 and φ_2, respectively. Using this method, time and spatial necking of a particular specimen can be predicted.

Considering the numerical approach of determining the FLD it is necessary to determine at which point and where on the specimen the material rupture occurs. To assure fast and reliable data processing a methodology for an automated evaluation of all specimens' nodes and their evaluated parameter were sought. It was deduced that by means of the evaluation of thinning and its acceleration in time it is possible to determine the necking of the analysed material.

The improved method used for the strain evaluation in a digital environment was performed in a three-step analysis, mostly an automated one in order to shorten processing time needed to obtain the major and minor plane strains of critical nodes [3].

Step 1: Analysis of sheet thickness in time, searching for critical nodes and the determination of their corresponding node numbers. In this first evaluation step, a huge amount of analysed data is already drastically reduced. Nodes with minimal thicknesses were inserted into the Abaqus post processor to obtain their thinning as a function of forming simulation time.

Step 2: Calculation of first and second temporal derivation of thinning for selected critical nodes. Due to a fast local change of sheet thickness at the necking point the thickness strain leaping changes its value. The acceleration of thickness deformation (second time derivation) defined as

$$\ddot{\varphi}_s = \frac{d^2\varphi_s}{dt^2} \tag{1}$$

was stored for all analysed nodes which are obtained as the output of the first step.

Step 3: A signal processing procedure was developed to purify data from all the stored nodes in order to obtain the critical node (location on the specimen) and the corresponding time when the necking at this node occurs. The node at which the maximum of

Table 1.
Material input data for selected sheet metals

	t_0 (mm)	E (MPa)	ρ (kg/m^3)	ν	R_p (MPa)	C (MPa)	n (1)	r_0 (1)	r_{45} (1)	r_{90} (1)
hot galvanised steel	0.64	207 000	7850	0.3	410	720	0.153	0.948	0.793	1.003
DDQ steel	0.5	207 000	7850	0.3	266	630	0.187	1.04	0.88	1.49
Al 3003	1.23	70 000	2750	0.33	36.7	197	0.24	0.538	0.588	0.452
Ti-alloy	0.9	143 000	4505	0.32	313	570	0.115	2.69*	4.0*	4.5*

* Comment: All coefficients of anisotropy represent r_{20} values except by the Ti-alloy where they are r_{10} values.

$\ddot{\varphi}_s$ first appears (at minimal time) was assumed as the node where the onset of necking started.

Nodes selected from each specimen's geometry in step 3 were considered to be at the necking point of the analysed material. The major and minor strains for these nodes were collected from the Abaqus result file and put into the FLD diagram. The entire three-step procedure was repeatedly performed for all simulated specimen geometries of each analysed material.

3.2. Materials

The presented three-step methodology for the determination of the FLD was performed on several different materials in order to verify the reliability of the proposed numerical approach. To assure different material parameters and analyse the reliability of the developed methodology for determining the FLD under different conditions, the following materials were selected:

- Material 1: Hot galvanised deep drawing sheet metal with a thickness of t_0 = 0.64 mm.
- Material 2: Low carbon deep drawing steel with good ductility and an initial thickness of t_0 = 0.5 mm.
- Material 3: The aluminium alloy 3003 with a thickness of t_0 = 1.23 mm is a soft aluminium alloy.
- Material 4: The last material is a Ti-alloy with an initial thickness of t_0 = 0.9 mm.

On the other hand, in all cases of numerical determination of the FLD the material data of the analysed material representing the input data for the FEM simulation were obtained experimentally with standardized uni-axial tensile tests. The measured and calculated material parameters are presented in Table 1.

3.3. FEM model

For the evaluation of the forming limit diagram in a digital environment with the experimental approach the Marciniak method was used. With this method it is possible to simplify the analysis of the processed data to the plain strain state of the observed area. As already presented in the prior chapter, with the Marciniak approach it is possible to determine the entire range of the FLD with the same tooling geometry and different specimen geometries. The strip-shaped specimens with various widths define different strain paths of the observed FLD – Fig 1.

The FEM model of the Marciniak test consists of three rigid tool parts – the die, the holder plate and the punch – as well as the specimen and the guiding plate which are considered elasto-plastic – Fig. 2.

When the simulation and an experimental set-up is planned the attention has to be put to higher ductility and thickness of the guiding plate in comparison to the analysed specimen. All formed materials, specimens and support plates, undergo the elasto-plastic Hollomon potential material law. At the FEM simulations the Coulomb friction law was assumed for all surfaces in contact.

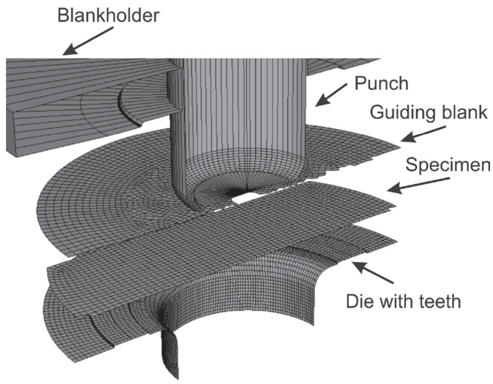

Fig. 2. FEM model of the Marciniak test

3.4. Experimental design, results and discussion

The experimental determination of the FLD underwent a forming procedure for six selected specimen widths which had to be identical with those selected at the numerical approach.
For the evaluation of the acquired frames obtained wth CCD camera with a frequency of 5 frames/sec a specialised program was used to enable a precise determination of the tearing limit. A deformation state defining the rupture limit at a particular specimen shape was analysed from the last grabbed frame before the material's tearing. The used program also enables the evaluation of the deformation path which has to be linear in order to properly determine the FLD.

The experimental evaluations of all four materials have shown different material behaviour from the necking limit onwards. While both steels have shown good ductility the difference between the necking and the tearing limit was very small at the Al3003 and Ti-alloy. Once all specimens for a particular material were evaluated with both approaches the comparative FLDs were constructed. The forming limit diagrams for all analysed materials are presented as follows: low carbon deep drawing steel - Fig 3, hot dip galvanised steel – Fig. 4, Al3003 alloy – Fig 5, and Ti-alloy – Fig 6.

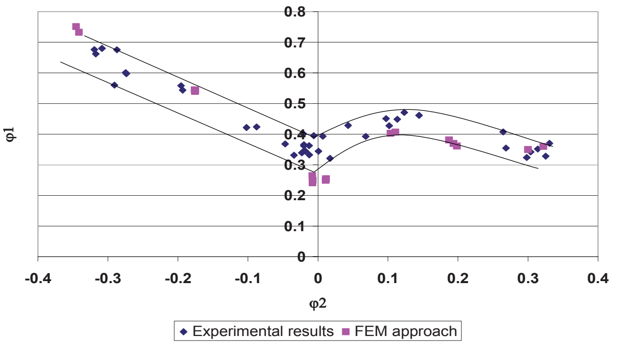

Fig. 3. Numerical and experimental FLD of low carbon deep drawing steel

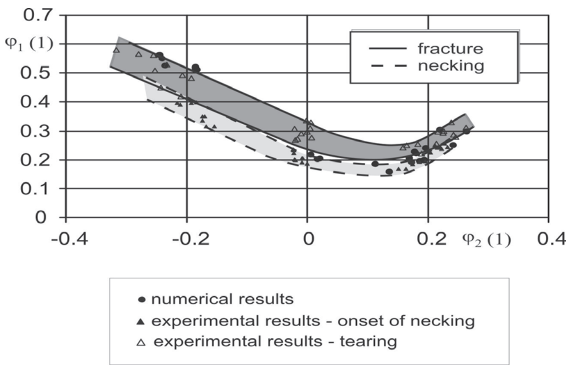

Fig. 4. Numerical and experimental FLD of dip galvanised deep drawing steel

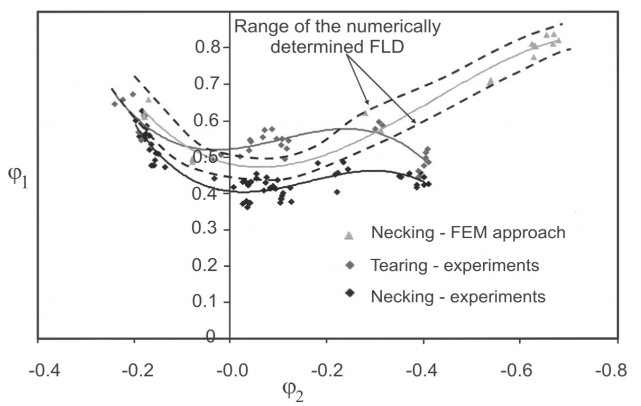

Fig. 5. Numerical and experimental FLD of Al-3003 alloy

The comparative evaluations have shown an excellent correlation between numerically and experimentally obtained FLD by both steels. Unfortunately, there are still some problems detecting the proper course of the FLD at the right side of the numerically determined FLD of the Al-3000 alloy where the evaluations of round specimens resulted in excessive necking values. The experimental determination of the FLD for the Ti-alloy has shown an interesting fact that this material merely resists a minor bi-axial load and has a very low level at the right hand side of the FLD. The comparison of the numerical and experimental approach is in this case very good as well.

4. Conclusions

The presented system for a numerical determination of the FLD was proven on four materials with different chemical compositions and mechanical properties. Comparative results of steel materials and Ti-alloy have shown a good correlation between the experimental and numerical results. In the case of the Al-3003 alloy the right side of the FLD is not as accurate as it has been expected. The improvements of the description of material models in the Abaqus for those materials are the first stage for better accuracy of the FLD determination. Furthermore, a wider range of different material thicknesses and qualities shall be performed to verify and consequently improve the reliability of the system. Some works in this field were already have already been performed with very thin tinplate materials and their evaluation of the digitally determined FLD is already in progress.

The final objective of the developed system for a numerical FLD determination is its wider application also for those materials where the experimental approach with available equipment cannot be applied.

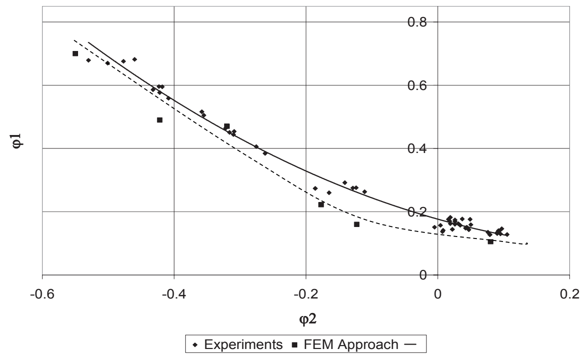

Fig. 6. Numerical and experimental FLD of Ti-alloy

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