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EXPERIMENTAL DETERMINATION OF FORMING LIMIT DIAGRAM

Dr.Sc. Amra Talić – Čikmiš,
Faculty of Mechanical Engineering
Zenica
Bosnia and Herzegovina

Dr. Sc. Tomaž Pepelnjak,
Faculty of Mechanical Engineering
Ljubljana
Slovenia

Dr. Sc. Suad Hasanbegović,
Faculty of Mechanical Engineering
Sarajevo
Bosnia and Herzegovina

ABSTRACT
Forming limit diagrams (FLDs) are a convenient and often used tool for the classification of the formability and for the evaluation of the forming process of sheet materials. Forming limits of sheet metal are represented in the forming limit diagram (FLD) occurring by various deformation states.
The paper introduces a experiment method for determination of forming limit curve for whole range of the FLD for sheet metal.
Key words: forming limit diagrams (FLD), experiment method

1. INTRODUCTION

In the industrial practice it is often important how the forming process is performed. It is necessary to define where the critical areas of necking and fracture are. The forming technology can be analysed before the tool is manufactured what leads to the savings of costs and time. If the forming limit for the particular product is known the process can be optimized. From this point of view the time is saved, the costs are reduced and the quality of products is improved.
The origin of analysis of the forming limits was given in the 1940ies. The first presentation, which includes a diagram similar to the typical FLD, was published by Gansamer in 1946 [1]. The concept of FLDs, as it is known today, was developed by Keeler in 1965 [2]. With the experiments Keeler realised the possibility to show a FLC for sheet metal in a coordinate system of two main strains, but only for the right side of contemporary known FLD ($\varphi_2>0$). This idea was extended by Goodwin [3] at the end of the 60's when the diagram was completed also for the left hand side with deformations of $\varphi_2<0$. The term "forming limit" was defined as a critical formability of metallic materials at the crack initiation. In recent 40 years a lot of research work regarding FLDs and their influencing parameters was done. At the beginning of the 1990s the research work was intensified by the start of enhanced practical application of FEA.
The forming limit curve for sheet metal represents a limit up to which the material can be formed before the cracks on the specimen occur. The curve is defined as a correlation between the first

principal strain φ1, which is major in the plane of the sheet metal, and second principal strain φ2, which is minor in the plane of the sheet metal (Figure 1).

Theoretical models determination FLD are rather complex and need a profound knowledge of continuum mechanism and mathematics. Theoretical calculated FLCs are not always in agreement with experimental data. Therefore some semi-empirical models have been developed. The first author of semi-empirical model was Keeler. The necessity to reduce the extensive analytical calculations and possibility of fast determination of the FLC in industrial environment led to study a precision and efficiency of definition of the FLC with experiment. To obtain various strain states during the forming process dissimilar tool geometries are required. Special methods for determination different stress states with only one tool geometry and various shaped tests are proposed.

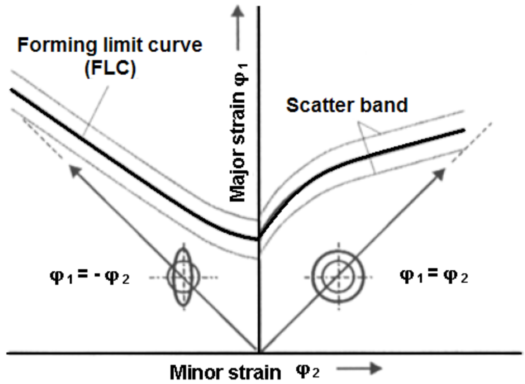


Figure 1. Forming limit diagram (according to Hašek) [4]

2. EXPERIMENTAL RESULTAT

Similar method to determine FLC (Figure 2) was introduced by Marciniak in 1973 [5]. In contrast to the Nakazima method remains analyzed region by Marciniak test flat during the experiment. Therefore, strains could be measured with only one camera, what represents an essential advantage of this method. Because to a danger of fracture which could appeared outside of the observed specimen area, a guiding blank is used. This prevents such failure. Efficiency of this method depends on geometry precision of guiding blank and a friction between test piece and guiding blank.

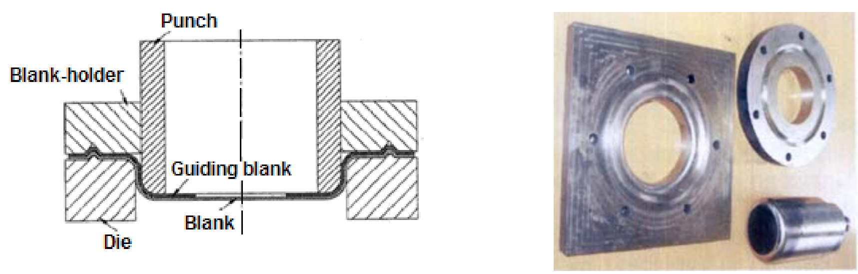


Figure 2. Tool for the Marciniak method[6]

Deformation analysis by both methods requires a grid system printed on the sheet metal surface. Once the deformed grids were measured with special microscopes but nowadays optical measuring systems with the CCD cameras are used.

System for experimental testing is shown schematically in Figure 2 as well as working parts of tools separately. Using the punch with a flat bottom, considered part of the test specimen keeps straight during deformation. Therefore, deformation can be measured by only one camera, which is an essential advantage of this method.
Define elasto – plastic material behaviour were obtained by uni-axial tensile test, and the experiments by the Marciniak test carried out and optical data acquisition equipment in Forming laboratory of Faculty of mechanical engineering in Ljubljana used. Measuring equipment (Figure 3) is designed for testing sheet metal thickness of 3 mm. The accuracy of the system is ± 2,5 % , at measuring diameter circles of *d=2 mm* (Figure 4).
The material used for experiments was St 13 (according to DIN standards). Basic mechanical properties of the experimental material are given in Table 1.

Table 1. Basic mechanical properties

direction	0°	45°	90°
$R_{p0.2}$	178,2	178,5	179,9
$R_{p0.5}$	196,7	196,5	196,4
R_m	321,9	323,6	321,3
A_{80}	35,7	36,2	35,2
A_g [%]	22,3	22,5	23,1
r10	1,64	1,53	1,78
r20	1,62	1,60	1,71
C[N/mm]	554,6	559,9	553,0
n[/]	0,214	0,216	0,213

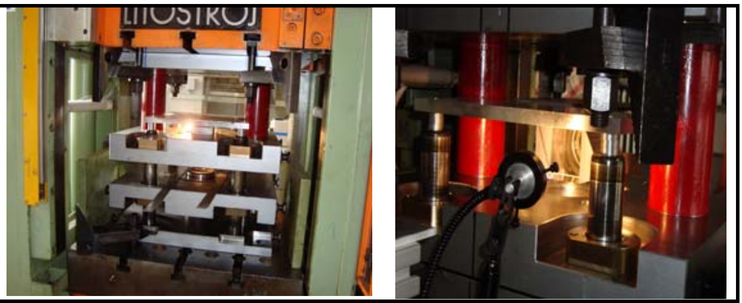
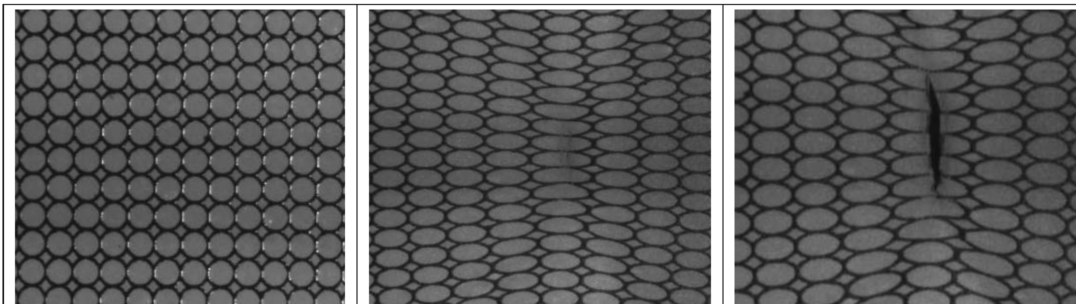


Figure 3. Equipment for testing and getting FLC diagram



No deformed network	Deformed network (before fracture)	Fracture

Figure 4. Monitoring of strain measurement network in the sample width w=40 mm [7]

The specimens, which were observed just before breaking, at all three specimens are defined longitudinal and transverse strain. FLD, which provides breaking, is a cloud over the state of deformation, which are calculated with respect to the sample just before breaking. The results were presented at Figure 5 (upper curve). Only elements of the measurement network were observed, through which the breaking is start, and the same, which lie nearly.
By included experimental specimens is possible predict, during performance of experiment, using the camera, start of local neck on material comparing deformation state on all three specimens. The literature suggests several criteria for determining the start of local necking. It is not possible to choose the best among them. All criteria are based on the fact that until the beginning of local necking, strain (deformation state) on the entire test specimen increasing quite evenly.

At the moment of beginning the local neck occurs to increasing the local deformation at the location of neck, while the strain on the rest of the specimen does not change. Start a local neck lies directly above the cloud strain states, represented in Figure 5 (lower curve).

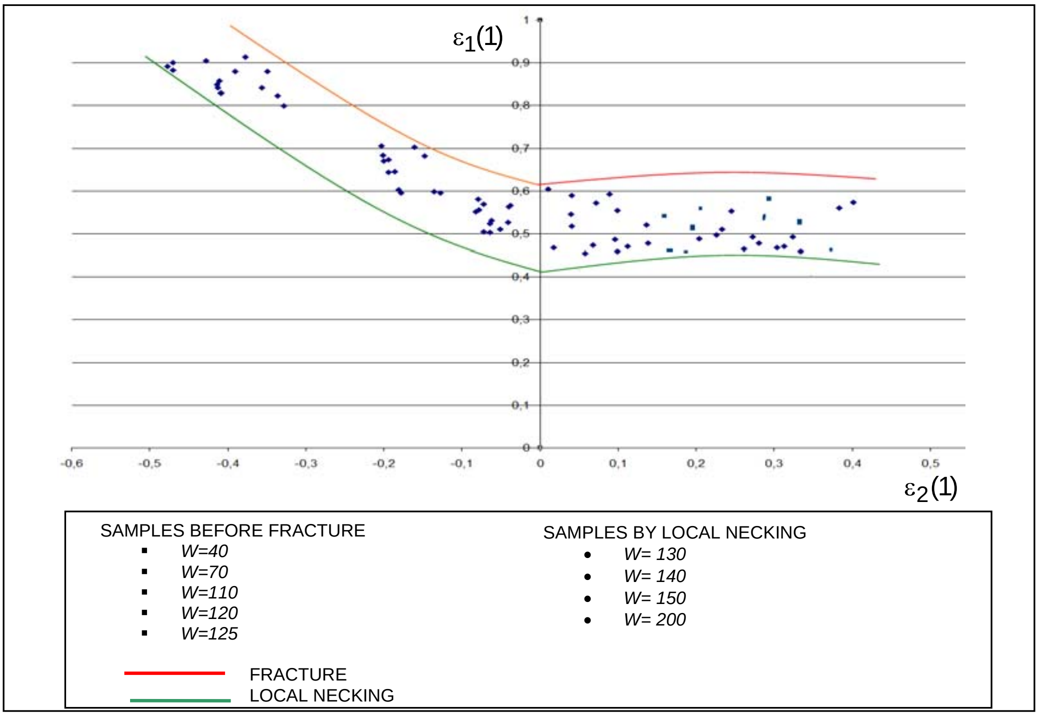


Figure 5. Experimental evaluation FLD[7]

3. CONCLUSIONS

The analytical solution, based on theoretical determination of necking and fracture limit is not applicable to a wide range of modern materials. Experimental determinations of FLD's are widely used, but unfortunately this concept is time consuming and also affected by the selected testing procedure. Most currently applied testing methods at present are Nakazima and Marciniak. Experimental determination of the FLD is very expensive and consuming. Modern production because very often resort to determining the limit curves of deformation in the digital environment. For this reason, then quality input data of used material is necessary.

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