

DETERMINING THE FORMING LIMIT DIAGRAM BY EXPERIMENTAL METHODS**RUSU Gabriela-Petruța***Faculty of Engineering, Department of Industrial Machines and Equipment, "Lucian Blaga" University, Sibiu, Romania, gabriela.rusu@ulbsibiu.ro***POPP Mihai-Octavian***Faculty of Engineering, Department of Industrial Machines and Equipment, "Lucian Blaga" University, Sibiu, Romania, mihai.popp@ulbsibiu.ro***CHICEA Anca Lucia***Faculty of Engineering, Department of Industrial Engineering and Management, "Lucian Blaga" University, Sibiu, Romania, anca.chicea@ulbsibiu.ro***POPP Ilie-Octavian***Faculty of Engineering, Department of Industrial Machines and Equipment, "Lucian Blaga" University, Sibiu, Romania, ilie.popp@ulbsibiu.ro*

Abstract: *In general, a large part of the time is devoted to the design and production of reliable parts where extensive knowledge is required for the design engineers to come up with an optimal solution for the tooling and sheet metal forming processes. Most of the time, the principle of trial and error is used to get the desired shapes for the products. This is because the prediction of deformations occurring in sheet metal elements is not available and is highly dependent on the geometry of the part, the tools and the deformation process. Prediction is limited by the proper location of necking, shear breakage, and puckering of the material. Searching for a robust deformation process by trial and error is expensive and inefficient. The use of numerical simulations provides engineers with an alternative efficiency for developing a tool and process to produce quality parts in a more efficient and lower cost. Computer simulation is an extension of theoretical science that is based on mathematical models. Such models attempt to characterize the physical prediction or consequences of scientific theories. The purpose of this work is to present the way of determining the forming limit diagram by various experimental methods.*

Key words: *constitutive law, forming limit diagram, Nakazima test, Marciniak test.*

1. Introduction

In industry, product life cycle management (PLM) starts with the processing of the necessary raw materials, passing through the stage of design and manufacture, maintenance, disposal and recycling [1]. A product can be defined from an engineering perspective as a functional shape made of several materials, which are given a set of properties and certain specifications [2]. The primary objective of product research and development is to determine the optimal way to manufacture it. Optimization criteria differ from one product to another depending on the requirements of each and can only be established by understanding the process through which it is produced. If the variable influences that occur during the process are not known (such as: friction coefficients, material properties or geometry) possible defects cannot be predicted. In the past, a number of approximate finite element analysis methods, also known as numerical simulation, have been developed for various plastic deformation processes.

The use of finite element analysis programs is possible due to advanced technology in being able to model the processing of materials, manufacture of product and its use until failure. Material design is more empirical, but new analytical methods are being developed to study material behaviors. Modern industry uses these methods to optimize and evaluate their product, so they can predict from the start how big the lifespan is and when it will fail. At the same time, this modeling can be used by researchers to better understand the physical phenomena that can occur in the material at all stages. In recent decades more and more researchers have studied this area and thanks to the development of mechanical theories, computer

technology and experimental techniques they have developed constitutive relations for solid materials and continued to improve them [3].

Engineering based on numerical simulation represents the third pillar of modern science and it represents an equality between theoretical aspects and physical experiments. Compared to physical experiments, engineering based on numerical simulation has the advantage of low cost, safety and efficiency in solving various problems [3]. In all these situations, a mathematical description of the material's behavior is necessary, i.e. a constitutive model. The classic models, such as: Hooke's Law regarding the elastic deformation of the material, the Navier-Stokes Law which refers to fluids and Fourier's Law regarding the transmission of heat by conduction; are the most common equations based on physical phenomena and experimental observations. However, even these experimental linear laws did not emerge without understanding the theoretical concepts of material behavior. Without it, one would not know what experiments should be performed and how their results should be interpreted. The purpose of these constitutive theories in continuum mechanics is to develop material models in accordance with universal principles that allow the formulation and analysis of mathematical problems, which are the basis of the prediction of material behavior that can be verified through experimental observations [5].

The constitutive model describes the response of a material to different mechanical and/or thermal conditions by providing the stress-strain relation, so that the determining equations, conservation laws and kinematic relations are formulated [2]. The constitutive models differ from one material to another (metals and alloys, polymers, concrete, wood, etc.) because the physical phenomena that determine their damage at the macroscopic level are also extremely different, for example: the constitutive equations that describe the behavior of water are very different from those that describe the behavior of a metal. Several different constitutive equations can be used for the same material, for example: the equations describing the properties of molten aluminum are different from those describing the properties of heated aluminum [2].

1. Forming limit diagram

The deformation limit of metal sheets is defined as the maximum level of deformation reached before the material breaks. The most common way to determine the yield strength of sheet metal is the yield limit diagram (FLD), known as the yield limit curve (FLC). This diagram is also known as the Keeler – Goodwin diagram, which was initially obtained from experiments to help designers assess the risks of necking and failure during plastic deformation processes [4]. It is currently used to predict failure in sheet metal deformation processes and has been implemented in most finite element analysis programs.

Figure 1 shows the areas bounded by the strain limit diagram. The two-axis involved in the diagram corresponds to major and minor deformations. Strains occurring in any area of the sheet blank are highlighted as a point on the strain limit diagram. Deformability of the sheet blanks should be analyzed by comparison of the positions of these points with the curves.

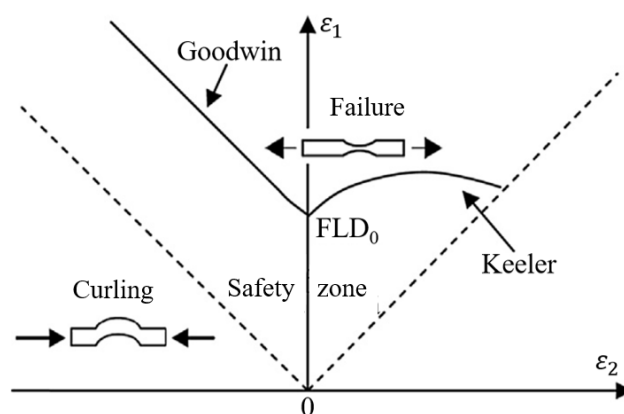


Figure 1: Forming limit diagram [4]

The forming limit curve represented in Figure 1 separates the safe area from the dangerous zones. This strain limit curve splits into two branches: "left" and "right". Keeler and Backhofen introduced the "right" branch which is valid for positive major and minor strains. Goodwin later completed the strain limit curve by adding the "left" branch for positive major strain values and negative minor strain. The "left" side

represents deformations that have a ratio ($\alpha = \varepsilon_1/\varepsilon_2$) which varies between the uniaxial tension ($\alpha = -0.5$) up to plane strains ($\alpha = 0$). On the "right" side the strain ratio is between the plane strain values and the full biaxial strain ($\alpha = 1$). The diagram developed by Keeler and Goodwin is shown in Figure 1 [2].

If the deformation value is located above the deformation limit curve, it means that bottlenecks and fractures occur in the material. They are located on the right and left side of the strain limit curve as was initially proposed by Goodwin and Keeler. According to the research done by Marciniak and collaborators in practice, scattered deformations were observed in the case of necking and instead of a single curve, a strip is used that delimits the area where necking is most likely to occur [1]. The intersection of the deformation limit curve with the major strain axis is denoted by FLD_0 and depends mainly on the coefficients of the uncrushed deformations and the thickness of the material [5].

Currently, depending on the type of limit deformations, different types of limit deformation diagrams are determined: for necking and for breaking. Two more types of strain limit diagrams have been discovered from experimental and theoretical research: the undulation limit curve defined by Havranek (Figure 2) [3] and the stress strain limit diagram defined by Arrieux. The latter does not depend on material deformations.

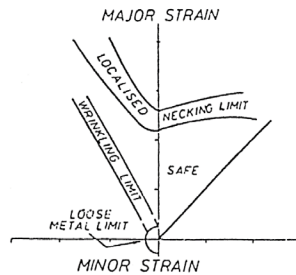


Figure 2: Ripple limit diagram [3]

To extend the application of these diagrams and 3D stress states researcher Simha and his colleagues presented a new concept called the stress-based extended strain limit curve ($XSFLC$) [SIM, 07]. The latter represents the equivalent stress and principal stress at the onset of necking during in-plane loading. Figure 3 shows the three variants of the strain limit curve concept, namely: strain limit curve based on strains (εFLC), strain limit curve based on stresses (σFLC) and the stress-based extended strain limit curve ($XSFLC$). The equivalent stress and principal stress are obtained using the formula:

$$\sigma_{eq} = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2} \quad (5.1)$$

$$\sigma_{principal} = \frac{\sigma_1 + \sigma_2}{3} \quad (5.2)$$

where σ_{eq} is the equivalent stress and $\sigma_{principal}$ is the principal stress which is assumed to be positive [6].

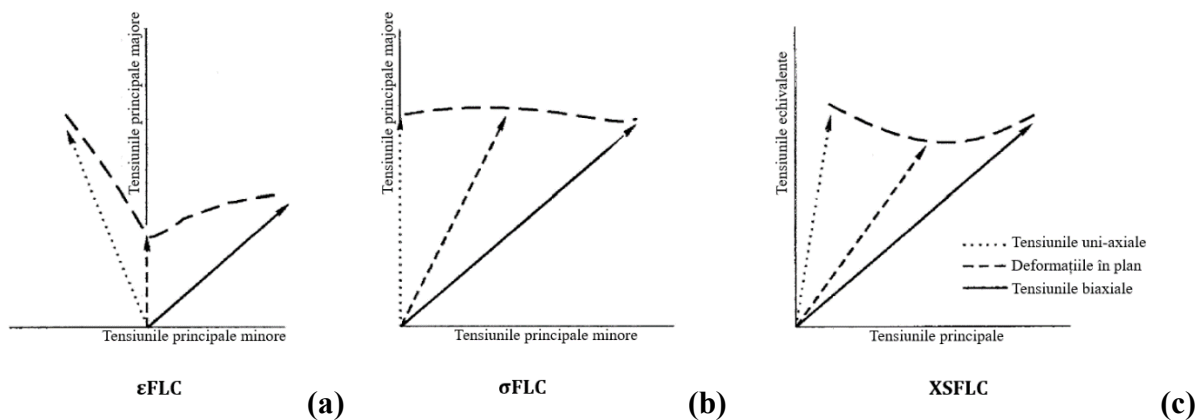


Figure 3: (a) strain limit curve based on strains (εFLC), (b) strain limit curve based on stresses (σFLC) and (c) stress-based extended strain limit curve ($XSFLC$) [6]

Most researchers have done experimental and theoretical analyzes that have shown that the maximum allowable strain limit depends on several physical factors including work-hardening, strain ratio, strain mode or load history, and plastic anisotropy induced by the cold rolling process. It has been established that this curve is sensitive to the subsequent operations on the steel sheets, in particular to the non-linear deformations occurring in the forming process. In industry, complex parts are produced which are usually manufactured by multi-step processes. Thus, the influence of strain history on the curve can be critical. In these cases, the deformation limit curve cannot be used to predict the behavior of the material during the deformation process [6]. In addition, numerous authors have shown that the deformation limit curve is applicable only for linear deformations [5], [6].

2. Determination of forming limit curves

To construct the FLC curves many researchers have conducted experiments and theoretical analysis to achieve this. During these experiments the admissible limit of deformations is obtained which depends on numerous physical factors including work-hardening of the materials, the strain sensitivity ratio, the stress history and the initial anisotropy given by the rolling process.

Determining the deformation limit curves can be done using one of the following experimental methods:

a) The tensile test allows the determination of the left-hand section of the strain limit curve. To obtain different points on this curve the specimens must be of different sizes and shapes. The advantages for tensile testing are the easy manufacture of the specimens and the use of a general-purpose testing machine; in addition, the samples remain flat during the experiment, which facilitates the measurements. However, only the negative side of the chart can be determined ($\epsilon_2 < 0$) [5].

b) Hydraulic Bulge Test was initially presented by Olsen. To vary the deformations appearing on the samples, a different shape of it is needed. One important advantage of this experiment is the lack of friction, and the disadvantage is that only the positive side of the diagram can be represented [7].

c) The Keeler test consists of using punches of different radius to find different points on the stress curve. The disadvantage of this test is that only the right side of the diagram is determined [7].

d) The Marciniak experiment is based on the idea of converting the vertical force into a biaxial force in the horizontal plane. This is done with a flat punch, and the sheet has a hole in the center. The hole expands radially as the punch moves. Punches with different sections (circular, elliptical, rectangular) are used to obtain different points on the diagram. The advantage of this test is that the break occurs on the flat bottom of the part and thus measurement errors caused by bends are eliminated. The disadvantage is represented by the shapes of the punch, the die and the limitation of the test to determine the positive side of the diagram. To surpass this disadvantage modifications can be done to the test procedure and to different pieces. [5].

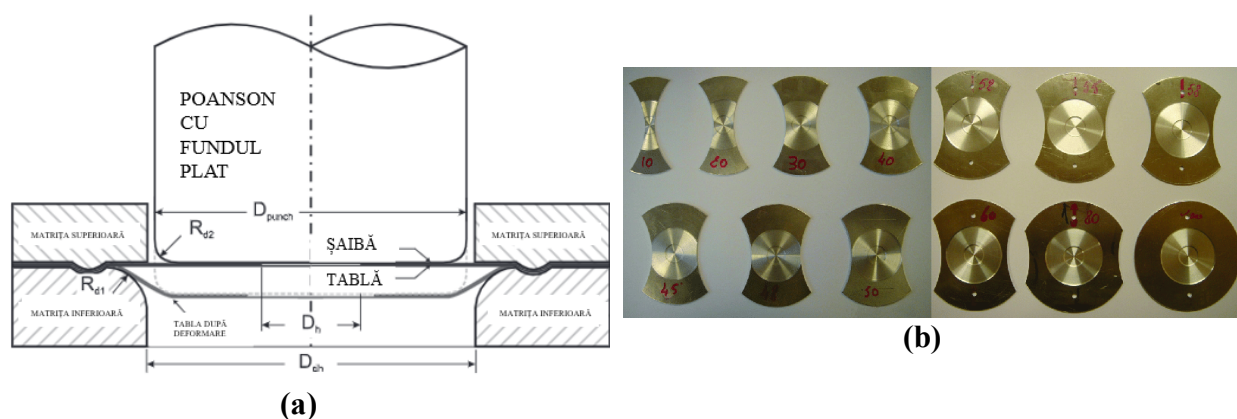


Figure 4: (a) Schematic diagram of the Marciniak test and (b) specimens used [5]

The Nakazima test uses the strain occurring during biaxial stretching to obtain the strain limit curve. This test consists in the deformation of rectangular specimens with the help of a spherical punch and a circular die. The specimens used have different shapes and their dimensions must correspond to the ISO 12004 standard. The advantage of this test is the simplicity of the instruments, the simple shape of the

specimens and the determination of the entire diagram. The disadvantage lies in measurement errors caused by the curvature of the punch [7].

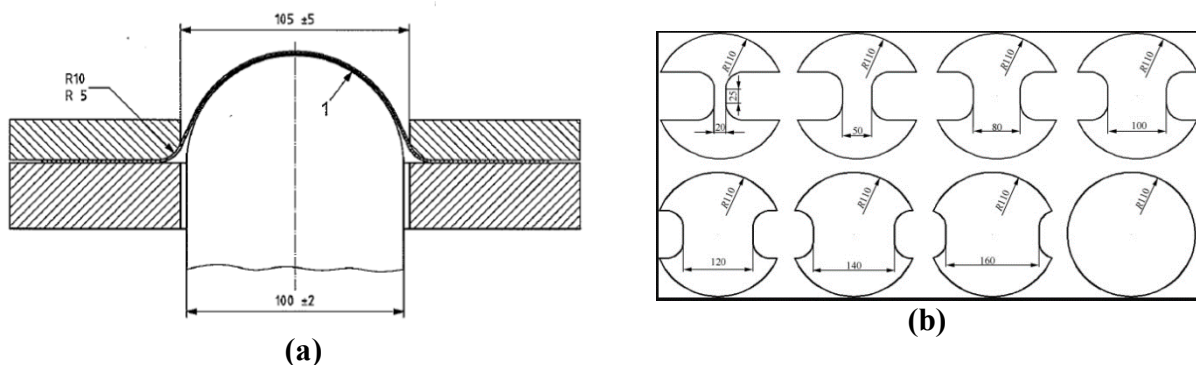


Figure 5: (a) Schematic diagram of the Nakazima test and (b) specimens used [7]

From the above tests the following are recommended: the Marciniak test or hydraulic bulge test (Hydraulic Bulge Test) to eliminate friction, the tensile test for simplicity and the Nakazima test to cover the entire diagram.

3. Conclusions and discussions

The study of the constitutive models that help to predict the failure of the material when it is plastically deformed is one of the current research fields. Determining the deformation limit curve can be done either experimentally or through various constitutive models. However, the nature of the analyzed process must be taken into account when we choose the way to determine it. In the case of deep-drawing, one of the best experimentally methods for determining the deformation limit diagram is the Nakazima test.

4. References

1. Kurkin, O., Januška, M., Product Life Cycle in Digital factory. Knowledge management and innovation: a business competitive edge perspective, *International Business Information Management Association*, pp. 1881 – 1886 (2010)
2. Barlat, Frédéric., Constitutive Modeling for Sheet Metal Forming (2005)
3. Zhou, Zhi-Dong., Zhao, She-Xu., Kuang, Zhen-Bang., An integral elasto-plastic constitutive theory, *International Journal of Plasticity*, 19, pp. 1377 – 1400 (2003)
4. Liu, I. – S., Constitutive theories: basic principles, *Continuum Mechanics, Encyclopedia of Life Support Systems, The UNESCO Publications*, 1, pp. 198 (2011)
5. Banabic, Dorel., *Sheet Metal Forming Processes*, Springer-Verlag, Berlin (2010)
6. Butuc, M. C., Teodosiu, C., Barlat, F., Gracio, J. J., Analysis of sheet metal formability through isotropic and kinematic hardening models, *Journal of Mechanics - A/Solids*, 30, pp. 532 – 548 (2011)
7. Ahmadi, S., Eivani, A.R., Akbarzadeh, A., An experimental and theoretical study on the prediction of forming limit diagrams using new BBC yield criteria and M–K analysis, *Computational Materials Science*, 44 (2009)