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THE ASSESSMENT OF THE FORMABILITY OF SHEET METAL USING NUMERICAL SIMULATION IN DEEP DRAWING PROCESSES

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ABSTRACT
Traditionally, the design of manufacturing technology and tool construction for metal forming processes relies on literature guidelines and the extensive experience of engineers. Today, the technology of deformation processing is in rapid development based on the application of computers, which enable extensive research and studies. This is also true in the area of sheet metal processing, as a specific group of 2D forming processes. Regarding of this, modern software for simulating the entire sheet metal forming process is increasingly being used. These software tools allow for a detailed analysis of the process, enabling the verification of preliminary design solutions and resolving potential dilemmas that arise during the design phase. These dilemmas most often relate to finding the most favorable relationship between material behavior and process parameters during forming, or the change of shape. This relationship, in recent decades, has been characterized by the concept of formability, which refers to the ability to form sheet metal without cracking, wrinkling, or other defects. Determining or estimating formability means predicting the material's behavior in a specific forming process in advance. One of the many methods used to assess formability is numerical process simulation. This scientific work presents an example of using numerical simulation as a useful tool for verifying the feasibility of manufacturing a redesigned filter housing according to the designed deep drawing technology, with a special emphasis on the direct assessment of sheet metal formability. FormingSuite software was used for simulating the deep drawing process.

1. INTRODUCTION

1.1. The Concept of Formability and Influencing Parameters

Deformation treatment processes significantly change the properties of metal materials. This is a result of changes in the material's structure. The extent to which deformation processing is possible depends on the initial structural state, chemical composition, and processing conditions, which are determined by the degree and speed of deformation, processing temperature, and stress state. The set of all influencing parameters on a material's ability or tendency to permanently change its initial metallic shape without causing cracks or other structural damage, or to permanently deform, is now referred to as formability or shapeabiliy. Deformability is a key term in the area of deformation processing and the application of metal materials shaped by deformation processing procedures, and it is based on the establishment of a relationship between the behavior of the material and the process parameters during the change of form from a preparation to a semi-finished or final product. Generally, deformability is influenced by numerous factors, but the most significant are the material type (chemical composition), structure, deformation degree, deformation speed (Strain Rate), processing temperature, stress state, and boundary conditions. In the general case, deformability can be expressed as a function of:

$$D = f\,(H_S, S_M, \varphi, \varphi', T_O, T_\sigma, G_u) \quad (1)$$

where is the following:
D - the deformability function, which is quantitatively expressed by the amount of deformation, H_s – chemical composition, S_M – materials structural condition, φ - deformation degree, φ' - deformation rate, T_O - processing temperature, T_σ - stress state, G_u - boundary conditions.
Therefore, it can be concluded that formability depends on two groups of factors: material and processing conditions. The first two factors (H_S, S_M) represent the material and define its initial or own deformability, while the other factors represent the processing conditions, as shown in Figure 1. Accordingly, the issue of examining and researching formability encompasses both the metallurgical and mechanical aspects. The metallurgical part involves the influence of chemical composition and structural state, that is, the possibility of creating such chemical compositions and structural states that will provide greater formability of the material. The mechanical part of the influencing factors is addressed by mechanical engineers, who find optimal solutions for the machining system and processing conditions to maximize the potential of the material's formability.

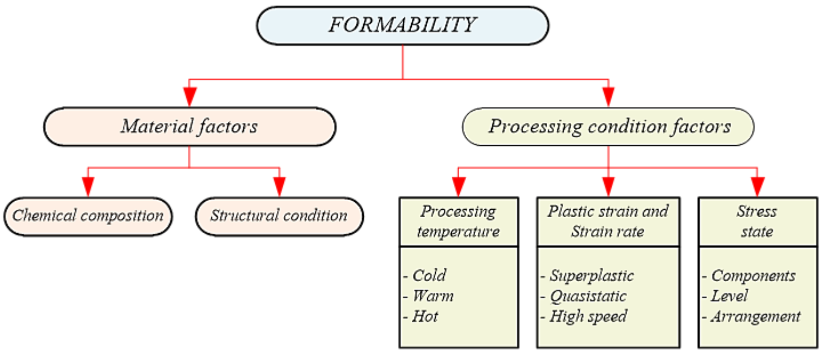


Figure 1. Factors affecting formability [1]

Although there is no universal and definitive test for assessing formability, nor are there more precise definitions of formability in the existing literature, formability is always quantitatively expressed by the maximum possible effective, or equivalent, deformation. Regarding of this, the use of the terms plasticity and ductility of materials is widely spread to express the plastic properties of metallic materials under certain standard deformation conditions. For assessing plasticity, the literature typically uses data on specific material parameters, based on which it is evaluated whether the material is more or less suitable for plastic deformation, such as the ratio of yield strength σ_t to material strength σ_m, the exponent of the flow curve n, cross-sectional contraction ψ, the anisotropy coefficient r, etc. Although we are dealing with the identification of simple plasticity parameters and specific recommendations regarding the suitability of materials for plastic deformation, it can be stated that these and similar approaches to the problem of material formability are now completely outdated. The reasons for this is the fact that the modern development of deformation processing technology is driven by the need to minimize material and energy consumption, focusing on cold deformation and more difficult-to-deform materials, as well as the production of parts with complex geometries and larger dimensions. Modern developments in deformation processing technology imperatively demand the search for ways and methods to make fuller use of material resources, which is precisely its potential formability. Numerous studies confirm that the realized stress state in the deformation zone has a decisive influence on the material's behavior in the process of plastic deformation concerning the manifestation of formability potential. This means that, by properly managing the deformation process and choosing the forming technology, it is possible to influence the stress state, and thus the material's behavior regarding the manifestation of formability potential from a mechanical perspective.

On the other hand, defining the concept of formability or formability as a property of materials that indicates their suitability for shaping or reshaping through one of the deformation processing methods has led to problems regarding the definition of formability criteria and the way it is expressed, as well as the development of an effective experimental methodology for its definition. In this regard, today two key approaches have been developed for defining formability. These approaches relate to the methodology for determining the forming limit curves or forming limit diagrams (FLC or FLD) for sheet metal forming and the introduction of a formability stress index, establishing a relationship between the effective or limiting deformation φ_{eg} and the formability stress index β in the form $\varphi_{eg} = f(\beta)$ through the boundary formability diagram in volume processing.

Both of these approaches aim to provide a general representation of the material formability problem, independent of a specific technological method. However, a larger number of available research papers examine and analyze the formability problem partially from the perspective of material behavior with respect to a specific technological method. It is evident that in this way, the material's behavior in relation to the observed process or forming technology can be most comprehensively expressed. Such an approach is also applied in this work, as the subject of the paper is focused on the software-based assessment of formability and the potential for efficient shaping through specific stages of the deep drawing process, one of the most significant sheet metal forming processes.

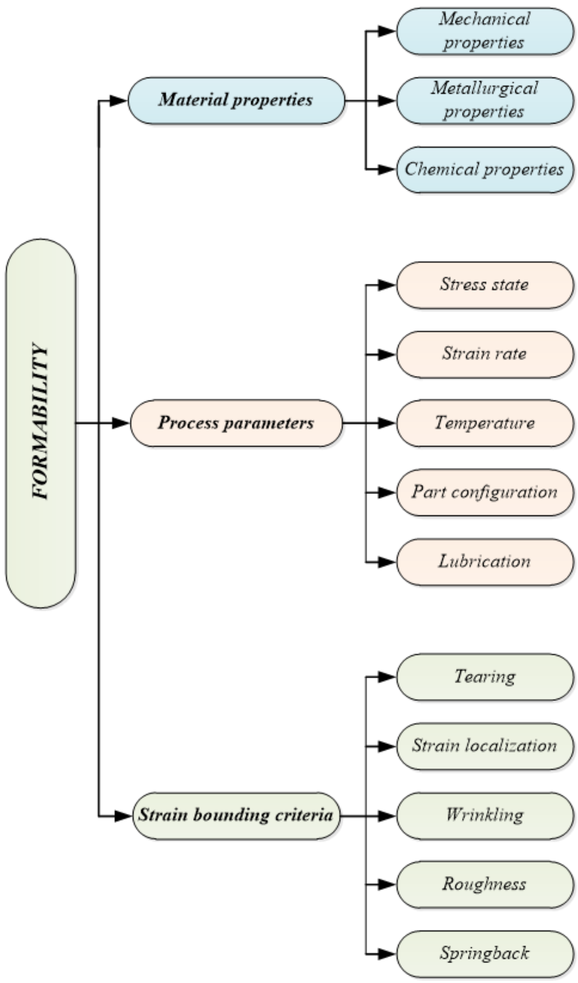


Figure 2. Influencing factors on sheet metal formability [2]

1.2. *Formability in Sheet Metal Forming*

The consideration and study of the material formability problem began with the technology of plastic deformation of sheet metal. As a measure of the relative ease with which sheet metal can be plastically deformed, formability actually represents its key property. Sheet metal formability can be simply defined as the ability of the sheet to undergo plastic deformation to a specific shape without any defects, including the rupture of the material's structure, excessive thinning, cracking, or tearing during forming. However, the problem of defining and determining the deformability degee is, unfortunately, much more difficult than the definition itself, as shown in Figure 2. Formability is a complex characteristic influenced by numerous factors. The broad division of influencing factors can be reduced to material properties, or material factors, process parameters, or processing conditions, and the limiting deformation or boundary conditions of the forming process.

A large number of different methods and processes have been developed for sheet metal forming. However, from the perspective of formability, or the ability to maximally form sheet metal without defects, the basic methods of sheet metal forming are considered to be bending, stretching, and deep drawing processes. Most sheet metal forming processes are actually combinations of stretching and deep drawing. Due to the complexity of the stress-deformation relationships during deep drawing, the issue of formability is most often defined as the problem of formability in deep drawing. This is due to the complex stress-deformation relationships in the material during the transformation of a two-dimensional blank into a three-dimensional shape (a vessel) during deep drawing. Specifically, as the sheet is pulled through the die opening, compressive stresses and negative deformations occur in the tangential direction, while tensile stresses and positive deformations appear in the radial direction. These complex stress-deformation relationships, combined with a number of other influencing factors during deep drawing, create a solid foundation for the occurrence of numerous defects in the final products. Therefore, by analyzing formability in deep drawing, the goal is to define the limiting deformations in the sheet plane that will not cause any defects in the formed parts, such as sheet tearing, wrinkling at the flange and wall of the vessel, the formation of ears, etc. Understanding the material's limiting formability enables efficient design of the processing technology with a minimal number of processing phases or operations, which ultimately allows for a reduction in overall production costs.

For assessing the suitability of materials for deep drawing, several methods have been developed, which can be classified into three groups:

- *Mechanical testing* for determining plasticity parameters,
- *Simulation methods* for testing,
- *Forming limit diagrams.*

Because of modern software tools for simulating forming processes are increasingly used to avoid lengthy and expensive testing, they are also being used more frequently for assessing formability through the use of the forming limit diagram. The application of modern software for modeling and simulating forming processes typically allows for the creation of FLDs, or direct assessment of sheet metal formability during individual forming stages. The Forming Limit Diagram (FLD) in sheet metal processing expresses the material's ability to deform under given processing conditions, and it is commonly known as the Keeler-Goodwin diagram. A simplified version of this diagram is shown in Figure 3 [3].

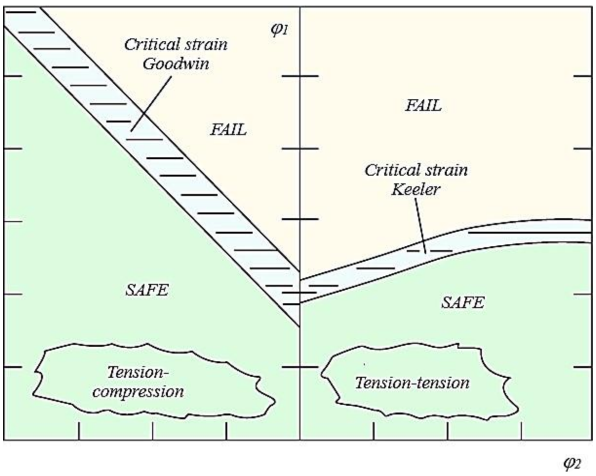


Figure 3. Forming Limit Diagram (FLD) for sheet metals defined by Keeler and Goodwin

It was developed to assess the efficiency of sheet metal forming, or to predict the limit of successful plastic deformation of the sheet. This diagram essentially represents the relationship between the principal strains $\varphi_1 = f(\varphi_2)$ at the moment when sheet rupture or tearing occurs, i.e., the relationship between the larger φ_1 and smaller unit strain φ_2 in the plane of the sheet.

It is most often determined experimentally, using various deformation methods such as stretching, deep drawing, etc. The effective application of this approach is especially enabled by the development of an electrochemical process for applying grids in the form of circles to the surface of the blank, through which the principal strains in two directions are easily determined after deformation. The axes of symmetry of the ellipses represent the main directions of deformation. The deformation continues until the first cracks appear. By measuring the magnitudes, logarithmic strains in the coordinate axis directions φ_1-φ_2 are obtained. By connecting the critical points, the forming limit curve (FLC) for the tested metal is obtained. The right side of the diagram corresponds to sheet metal forming processes such as stretching, while the left side of the diagram covers deep drawing and some other forming processes. In the simplified FLD shown in Figure 3, the forming limit curve is not displayed, but rather a shaded zone, which represents a safety area. No defects should appear below the lower line of the zone. The lower line in the diagram marks the beginning of deformation localization, while the upper line marks the point of rupture. The safe processing area represents a combination of larger φ_1 and smaller φ_2 strains, which lie below the boundary lines. In practice, when creating the FLD for a specific material and forming process, the forming limit curve is formed by connecting the critical forming points. All points below the forming limit curve represent deformations where no cracks will occur in the material, while points on or above the curve indicate deformations where cracks will appear in the material during forming.

2. DESIGNING THE TECHNOLOGY FOR FORMING A FILTER HOUSING

The given product is the housing, or the oil filter cup, made of DC04 steel sheet (Č.0148) with a thickness of *s= 0,63 mm*, which is shown in Figure 4. Based on the calculations performed according to the procedure presented in published literature, it was concluded that the product can be efficiently manufactured in 3 deep drawing operations, with an additional operation of initial blanking of the sheet strip, two supplementary operations for shaping a hexagonal profiled cap SW 30, and a final operation of trimming the flange of the finished product. The technology for deep drawing was designed in a classic way, satisfying all the necessary principles for determining the blank diameter, the dimensions of the products by forming stages, as well as the analysis of forces and deformation work. Figure 5. presents the shapes and dimensions of the products by forming stages.

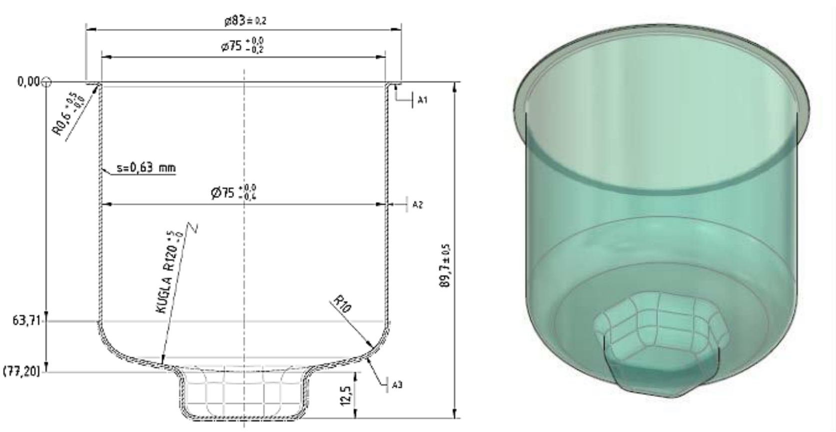


Figure 4. Dimensions (left) and filter housing model (right) [4]

Before the actual process of dimensioning the working elements of the tools for the individual forming stages and the design of the working elements and tool assembly, a numerical simulation was carried out using the finite-element-method (FEM) to verify the possibility of efficient forming and manufacturing the filter housing from a single piece according to the designed technology.

3. NUMERICAL SIMULATION AND EVALUATION OF SHEET METAL FORMABILITY

Numerical simulation is a very powerful and widely applied tool for the numerical simulation of forming processes. Thanks to the rapid development of computer technology, many commercial software packages have been developed, based on the finite-element method, for solving problems in deformation processing procedures.

Numerical simulations of forming processes, in addition to optimizing processes without the need for prior tool manufacturing and trials, also imply software verification of the possibility of producing parts according to the designed technology, and avoiding expensive trials and unnecessary prototype production costs.

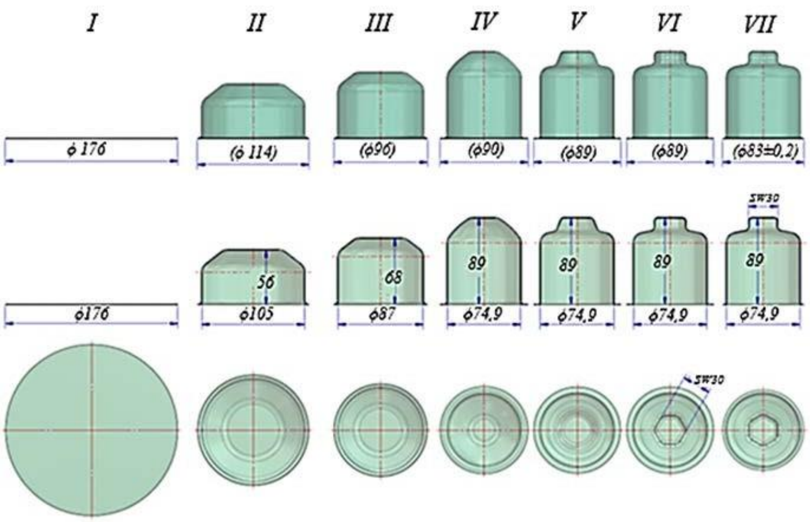


Figure 5. Shapes and dimensions of the workpieces by stages of forming [5]

To verify the possibility of producing the filter housing from a single piece, according to the redesigned manufacturing technology, a numerical simulation was conducted. For simulating the individual forming stages, the finite-element-method was used, and the simulation was performed through the user-friendly interface of the FormingSuite software. FormingSuite is a specialized software package developed by Forming Technology Incorporated for computer simulation of sheet metal forming processes.

The aim of the numerical simulation conducted for the deep drawing stages was to obtain reliable information, i.e., to assess the possibility of successful forming with the display of critical points on the products, changes in material thickness, and identification of achieved deformations in the forming limit diagram of DC04 sheet metal during the forming process.

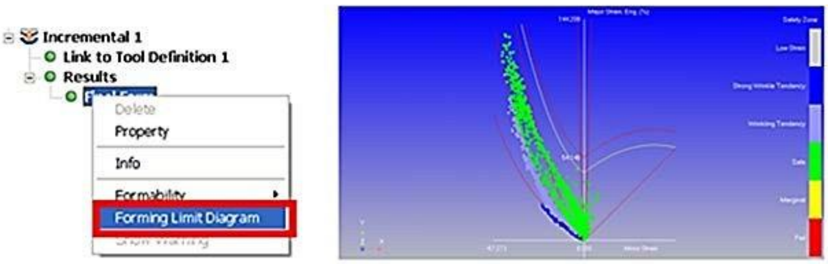


Figure 6. Forming limit diagram FLD in FormingSuite software

The software allows for incremental analysis, and within the formability menu, it enables the creation of the forming limit diagram (FLD) with a review of safety zones during deep drawing. The process of creating the forming limit diagram for DC04 steel in the FormingSuite software, with the display of safety zones, is shown in Figure 6 [6]. These zones are differentiated by colors and are defined as safe, low strain, wrinkling tendency, strong wrinkle tendency, marginal, excessive thinning, shear and fail.

In addition, for each forming operation, the results of the FEM analysis show the distribution of sheet thickness and the FLD with values for the greater and lower surface deformation and the position of their combinations in the forming limit diagram. A simple analysis of these graphical representations allows for conclusions to be drawn regarding the possibility of efficient forming according to the designed technology for a specific phase of shaping. A portion of the systematized results from the numerical simulation for the initial and final phases of shaping is presented in Tables 1. and 2., which show the shapes and dimensions of the products, the distribution of safety zones and deformations, as well as the forming limit diagram.

By analyzing the simulation results by shaping phases, it can be concluded that the forming of the filter cup according to the defined shape and calculated dimensions is feasible and entirely reliable from the perspective of safety zone distribution, permissible thickness changes, and the combination of main deformations in the plane of the sheet, all of which remain below the FLC curve.

It is noticeable that in FLD displays it is dominated by:

- *Green color or safe zone*, which represents the area below the forming limit curve where no defects occur.
- *Light blue color or wrinkling tendency zone*, which indicates the possibility of slight thickening of the sheet with a potential occurrence of wrinkling.
- *Blue color or strong wrinkle tendency zone*, which represents a combination of higher and lower deformation in the sheet plane that leads to thickening of the sheet and a very likely occurrence of wrinkling. Increasing the force of the sheet holder can eliminate this phenomenon.

Table 1. Key Results of FEM simulations in the initial stages of forming

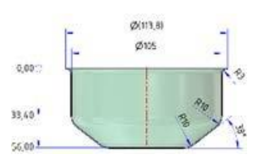
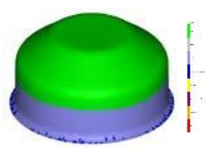
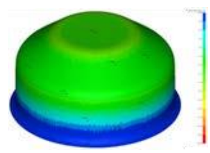
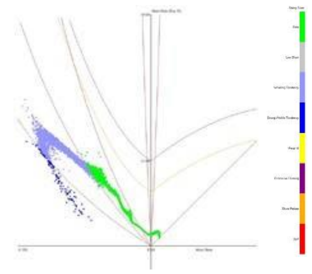
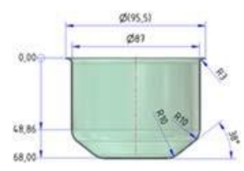
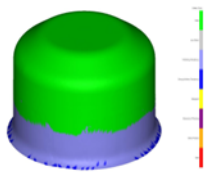
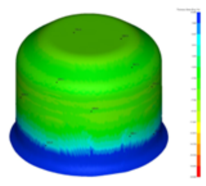
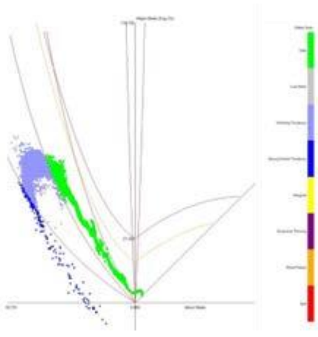
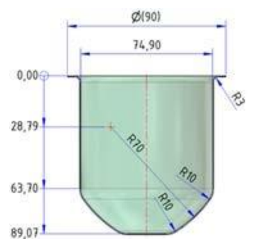
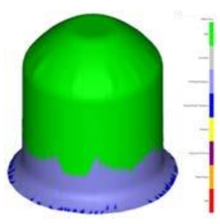
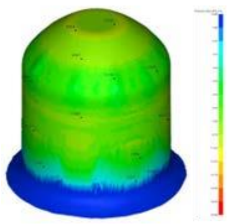
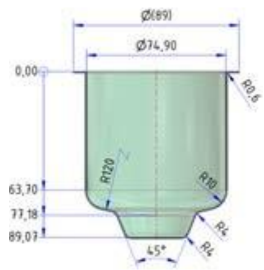
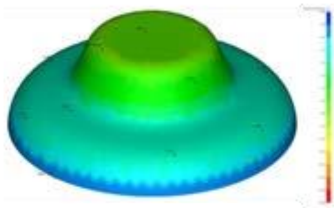
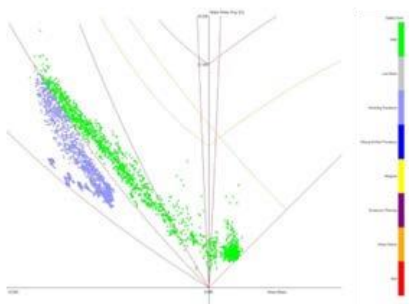
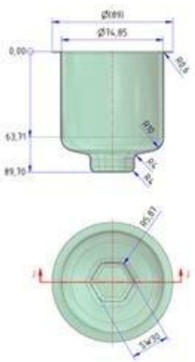
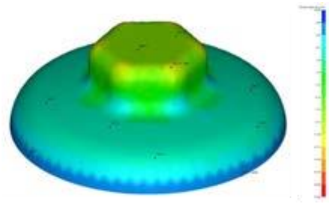
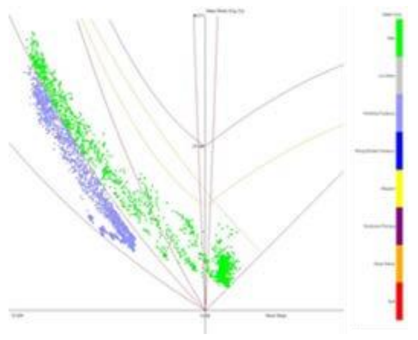
Forming Stage	*Shape and Dimensions of the Product*	*Safety Zones*	*Thickness Distribution [%]*	*Forming Limit Diagram (FLD)*
1.				
2.				
3.				

Tabela 2. Key Results of FEM simulations in the final stages of forming

Forming Stage	*Shape and Dimensions of the Product*	*Thickness Distribution [%]*	*Forming Limit Diagram (FLD)*
4.			
5.			

From the deformation distribution by thickness in the simulation, it can be concluded that the maximum thickening of the sheet (blue color in the simulation display) is up to 10%, while the maximum thinning of the sheet (transition from green to yellow color in the simulation display) ranges within 10%. These are the allowed values of thickness change during deep drawing.

4. CONCLUSION

Material formability, as the ability or suitability for shaping without defects, is today considered one of the fundamental technological properties of metal materials, and its definition is highly complex. Due to a variety of specifics and certain sensitivities associated with the area of sheet metal forming, the issue of sheet metal formability is treated separately. Sheet metal forming contain a wide range of methods, with one of the most significant being deep drawing, for which it is crucial to understand the material's tendency to be shaped by this process.

Although the ability of a metal material for deep drawing, or simply drawability, is expressed as the maximum ratio of the initial die diameter to the inner diameter of the drawn part, known as the Limit Draw Ratio (LDR) or maximum drawing coefficient (β_{max}), today, for a more comprehensive assessment of this property, the main tool used is the Forming Limit Diagram (FLD). This diagram has become a highly successful and widely used tool, enabling the achievement of optimal and rational production concepts. Understanding the material's limit formability allows for the efficient design of technological processes with a minimal number of processing phases or operations, ultimately reducing overall production costs.

For constructing FLD, various experimental methods are typically used, requiring a broad range of sheet metal forming tests and expensive equipment. By applying computers and modern simulation software, it is now possible to easily verify preliminary design solutions and assess sheet metal formability through FLD, without the need to create tools and conduct trials, resulting in significant financial savings and reduced production time. Software simulation with FLD representation by forming stages and the methodology of its application is one practical example, based on which the technology for reliably forming filter housings from a single part was adopted.

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