FORMING LIMIT DIAGRAMS AS AN IMPORTANT INDICATOR OF PROGRESSIVE HIGH-STRENGHT STEEL SHEETS FORMING

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Abstract

Forming limit diagrams (FLDs) of thin sheets are no novelties in the scope of forming. With new (modern) oncoming progressive materials, mainly for the automobile industry, it is once again that these limit diagrams gets to the forefront of awareness and interest of professionals who are engaged in the production and processing of materials. In addition to a number of different tests of formability (compressibility), these FLDs are in fact a very important part in point of view of thin sheets forming evaluating.

Key words: stamping, forming limit curve, press ability, forming limit diagram

INTRODUCTION

For possibility to clearly determine to what extent are deformation abilities used for deep drawing of the sheet, it is necessary to know real tensile deformations for all stress statuses that occur in surface forming. In real, the FLD is used in relation to the valuation of material plasticity (for sheet) is comparing their plastic properties in the extension strain state, but is also used in relation to a comprehensive analysis of the deformation product. These limit diagrams are part of an overall system of deformation product analysis, which is primarily used even in pre-production stages of production. Given type of diagram shows dependence of ultimate main deformation „major strain“ (vertical diagram axis „φ_1“) on the least main deformation „minor strain“ (horizontal diagram axis „φ_2“) in the plane of examined sheet. Where $\varphi_2 \leq \varphi_1$ are main normal logarithm deformations, and φ_2 is perpendicular to φ_1.

$$m_\sigma \left(m_\sigma = \frac{\sigma_2}{\sigma_1} \right) \qquad (1)$$

Individual strain states are shown by indicator m_σ in formula (1) where σ_1 and σ_2 are main normal strains in the sheet's plane [1, 2].

FLDs are normally specified for strain status, where usually becomes cracks in the process of drawing. It describes the impact of strain for sheet plasticity at specific speed conditions given by temperature. Limit deformations in diagrams are in discreet points range, but most often are processed in forming limit curve (FLC) [3, 4].

Forming limit curve (FLC) shows on diagram two areas of inadmissible (up the curve) and admissible (under curve) deformations in term of acceptable definition about limit state. FLC shows limit of this two areas and determines critical deformations for given limit state. Safe drawing zone – area under limit deformations curve correspond to the area of admissible deformations and area up the curve shows a zone of inadmissible deformations in drawing process [5].

EXPERIMENTAL-MATHEMATICAL METHODS OF FLD DETERMINING

Keeler-Goodwin theoretical FLD

While determining this FLD we also consider the loss of stability in tensile strength (dF = 0, where F is the deformation force). Basics of theoretical solution are in pursuance of scientific works of Swift a Hill. Hill´s thesis describes the reflection, that in the area of major plastic deformations on one axis strain it arises local reduction of sheet in its thickness direction, which can be imagined as shallow groove. He determined conditions of its formation, that increment of deformation in the direction along this groove is null and that it can be show up only for strain states between deformation plane and simple shear. That means the left part of mentioned FLD[2].

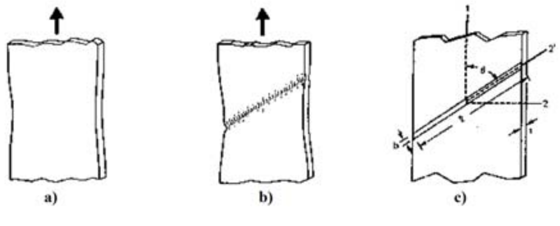

Fig. 1 Diffuse neck (a) and localized neck (b) coordinate system (c) [6]

Swifts reflects to another type of stability loss in tensile strength. It deals with diffused or advanced stability loss, which can be able to describe the effect of deformation localization for individual strain states, where Hill mentioned, that local reduction won't appear. These assumptions with two type of stability loss are principally shown on the schema at fig. 1. Based on wide research, there were derived formula for calculating the limit deformation curves which were also known as „Theoretical Keeler-Goodwin FLD“.

For empiric intended values of real limit deformation, Keeler designed the area (strain-strain) right part and Goodwin (strain-stress) left part of the forming limit curve [2].

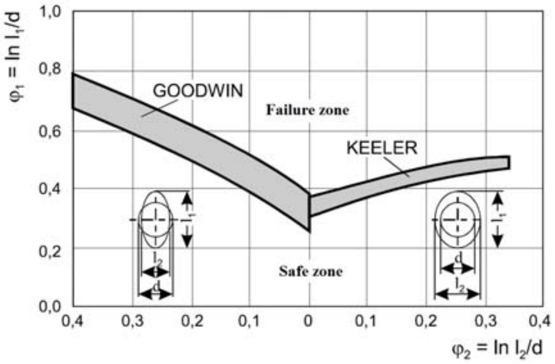

Fig. 2 Keeler-Goodwin FLD [7]

Next formulas (2) - (4) shows theoretical Keeler-Goodwin of forming limit curve in the left part of FLD for local stability loss (3) and the right part of FLD for diffusion stability loss (4) [2]:

$$\varphi_1 = \frac{D_1}{D_1 + D_2} n, \tag{2}$$

$$\varphi_2 = \frac{D_2}{D_1 + D_2} n, \tag{3}$$

$$\varphi_1 = \frac{D_1}{A^{\frac{1}{2}}.D^{\frac{1}{2}}} \varphi_i, \tag{4}$$

where

$$\varphi_1 = \frac{A^{\frac{1}{2}}.D^{\frac{1}{2}}.A_{1212}}{F_a.D_1 + F_b.D_2.m_\sigma} n,$$

$$F_a = (A_{1212}.D_1 - A_{1112}.D_2),$$

$$F_b = (A_{1212}.D_2 - A_{2212}.D_2),$$

A_{ijk} and D_x functions r_0, r_{45}, r_{90}, α, m_σ [2].

Determination method of LDC by "MC" theory

The practice of drawing shows, that often can be used the deformation exceeding the tensile strength of material for forming process. And at the same time that local narrowing thickness (the formation of cervical) actually occurs even when strain states that correspond to the right side of FLD (φ_1 and φ_2). Mentioned neck and questions about its formation formed Marciniak and Kuczyňski (MC theory). This concept, which were proposed by them, consider the local neck formation because of nonhomogenity (texture, nonhomogenity of structural elements, noneven sheet material or grain size changes) in forming sheet. Mentioned stability loss by local reduction will cause also local change of strain state towards to deformation plane, which can be shown on the plasticity curve very simple [8].

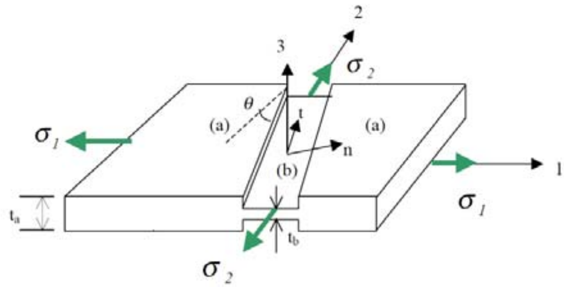

Fig. 3 Sheel element with noneven thickness [9]

Basics of this MC-theory can be described the most easily is follows: Calculation is based on the existence of starting noneven thickness or other sheet nonhomogenity, which causes narrow areas formation in the drawing process. Impact of mentioned factors can be described by behaving of final „groove“, which is shown on fig. 3 and its direction is perpendicular to direction of maximal normal real deformation φ_1 and is characterized by weaken parameter

$$T_0 = \frac{t_b}{t_a} \tag{5}$$

where

t_b = starting sheet thickness inside the groove,
t_a – starting sheet thickness outside the groove [5].

Hardening speed of material started to decrease with increasing degree of deformation (in area "b" faster). Difference of real deformation gets increased in the φ_1 direction for areas ($\varphi_b > \varphi_a$) "a" and "b" and increase rate of deformation $d\varphi 2 / d\varphi_1$ is getting to value zero. Following that, it means that deformation heads to plane deformation status ($d\varphi_2 = 0$, $d\varphi_1 = d\ \varphi_3$) and till the end it gets the disruption of formed sheet in the „b“ are because of deformation localization. Maximal deformation which is in the „a“ area in the moment of „b“ area deformation is then taken as a limit deformation value [10].

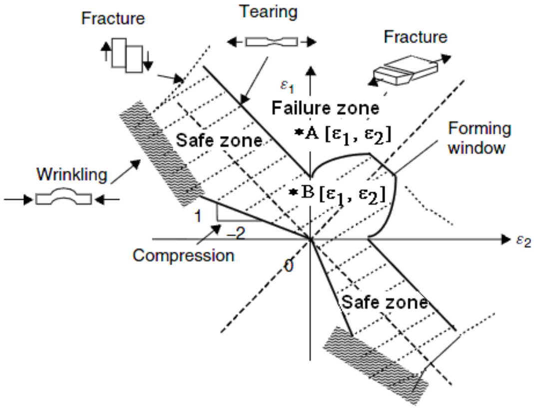

Fig. 4 FLD - Stress strain state in sheet plane [7]

Determination of FLC by "HTR" model

This modification of criteria for maximal force, which is presented as Hor, is based on the reflects and assumption, that the state of plane deformation exist. It is made by deformation localization in the direction of sheet thickness. Follow up the state change of strain, in the local reduction place it gets the effect of additional hardening, which does not occur outside the local reduction [10].

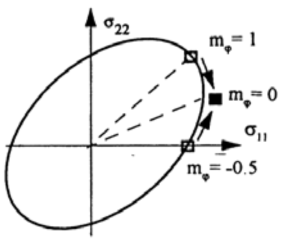

Fig. 5 Schema shows the effect of additional hardening [9]

Tension σ_{11} of formula (6) depends on deformation increment $\Delta\varphi_{11}$ but also depends on deformation state – formula (7). Material hardening in the deformation process is described by inherent deformation resistance [11].

$$\frac{d\sigma_{11}}{d\varphi_1} = \sigma_{11} \qquad (6)$$

$$\sigma_{11} = f\left(\Delta\varphi_{11}, m_\varphi\right) \qquad (7)$$

Mathematic formulation of modified criteria of maximal force (HTR) is as follow:

$$\frac{\partial\sigma_{11}}{\partial\varphi_{11}} + \frac{\partial\sigma_{11}.\partial m_\varphi}{\partial m_\varphi.\partial\sigma_{11}} \geq \sigma_{11} \qquad (8)$$

Advantage of the HTR is the possibility to use not only classic Hills „quadratic“ plasticity condition for isotropy or anisotropy material, but also in possibility to use Hills „no quadratic“ plasticity conditions by Barlat-Lian, which allows to properly modification the plasticity curve shape [2].

Determination of FLC by ductile fracture criteria

This method of FLC calculation is based on ductile fracture reach, so that from second limit definition of limit state. Criteria of limit state is the breach of material, so the moment when system loss its thermodynamic stability.

Fracture criteria of stability loss shows the critical (limit) values on inside parameters, which gets to the large joining of inside cavities in the whole section of material. This criteria is based on static interpretation through shear process of inside cavities joining, which increase its size while in preceding plastic deformation [11].

Simplified condition of ductile fracture by formula (9)

$$K_{cr} = \left(1 + m_\sigma\right)\sigma_1^2 \qquad (9)$$

K_{cr} – constant is adjusted form of „fracture“ stress parameter. This constant contains a lot of data, for ex. final size of cavity data, inclusion volume size, cavity growth speed and speed around it an so on. And it shows the characteristics of inside material behavior [2].

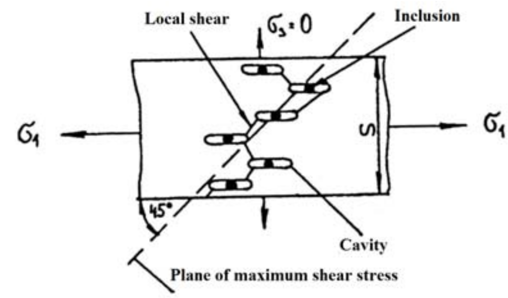

Fig. 6 Schematic view to shear loading [11]

CONCLUSION

The development of new progressive materials is currently the highest priority in the automobile industry. The designers are trying to reduce the weight of the structure to the lowest values just using modern AHSS and UHSS steels.

Through them it will increase the strength and reduce the thickness of the structure which is very important in protecting vehicle passengers when unforeseen collisions. On the other side it lower the values of formability for these materials. For this reason it is necessary to define the limit values of deformation, in order to avoid cracks, bottleneck, cracking, curling etc., in forming process. If we know the diagram of limit deformation of the steel sheet, we can assess its suitability for drawing. Therefore, the necessity of determining the forming limit curves (FLC) for progressive high-strength steel sheets is very important.

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