FORMING LIMIT INDICATORS IN METAL FORMING

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Summary: *Precise information on forming limit indicators is very important in designing the technological processes of metal forming. The significance of stress state and strain history for limit strains realization is emphasized above all. For the case of upsetting, indicators in the system of principle surface strains are specified, as well as classic example of FLD, as a dependence of limit strain on stress ratio coefficient. For the case of sheet metal forming – deep drawing, the example of determining FLD at classic and two-phase - proportional forming – is shown. The specified experimental results are related to the area of stretching and the area of pure deep drawing of axis-symmetrical pieces.*
Key words: *Metal forming, Forming limit, Strain path, Upsetting, Deep drawing*

1. INTRODUCTION

When designing the technological processes of metal forming, it is extremely important to understand the concept of limit formability, which can be defined as the ability of materials to achieve permanent shape changes, i.e. ability of materials to accomplish maximal strains in the given forming conditions. The criterion for defining limit formability can be either fracture or forming instability (appearance of localizations). The influence of certain factors on the value of limit strain, as a numerical indicator of materials formability, can be implicitly expressed, by formability function [1]:

$$D_M = \varphi_e^l = f(H_M, S_M, T_o, \dot{\varphi}, T_\sigma) \quad (1)$$

where:

D_M – material formability,

φ_e^l – limit strain,

H_M – type of material, defined by a particular chemical content,

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S_M – structural state of the material,

T_o – forming temperature,

$\dot{\varphi}$ – strain speed,

T_σ – stress state determined by stress tensor.

For established and unchangeable forming conditions (material, speed, temperature), the possibility for changing limit strain values is, obviously, most efficiently influenced by the change of stress state, i.e. $\varphi_e^l = f(T_\sigma)$. For that purpose, executive elements of the forming system should be created in such a way that the available formability potential could be exploited up to its maximum. Control of forming system – tools construction, geometry of initial work piece shape and tribological conditions – should have, as a final result, generation of appropriate stress components in the pressure zone and avoidance of stress in tension zone.

At experimental determining of formability properties, it is necessary to comply with the conditions of so called „strain history". This means that limit strain values must be established in conditions which satisfy proportional forming rules. Such stress is realized when outer forces, which load the observed element, increase proportionally to one general, constant parameter, from the beginning of forming. Due to this, the ratio of diagonal components of stress tensor deviator (and principle stresses ratio, as well) is a constant value. Also, the concurrence of main stress and strain axes must exist throughout the process. In more complex cases, these conditions are not fulfilled, so the entire process should be divided into several phases – stages, within which the specified conditions are satisfied.

2. BULK DEFORMATION PROCESSES

In the area of bulk metal forming, there are two methodologies for defining forming limit diagram. The first methodology is related to determining the limit forming curve, as principle strains function in the moment of material fracture $\varepsilon_2 = f(\varepsilon_1)$. Experimental determining of dependence $\varepsilon_2 = f(\varepsilon_1)$ is performed by measuring the elements of measuring grid per forming phases (stages) in fracture zone. At cylinder compression by flat dies, measuring zone is marked in meridional plane of the piece. Figure 1 shows the forming limit diagram (FLD) for the case of compression of cylindrical specimen by conical dies [3]. According to the obtained results, the dependence among main strains can be presented in the form of expression ε_2 = 0,15-0.5ε_1. Dependence ε_2 = - 0.5 ε_1 is valid for completely homogenous– uniform forming.

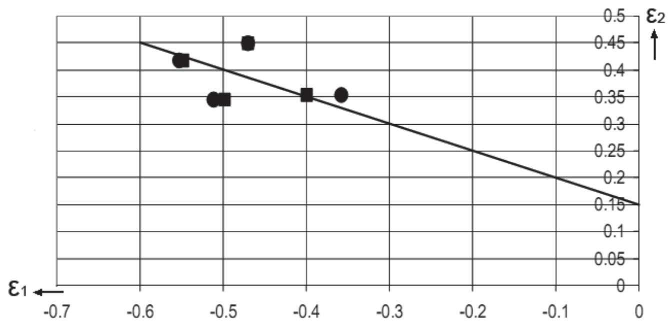

Fig. 1. *Limit strains curve at compression by conical dies*

The second procedure is based on establishing the connection between effective limit strain and stress state indicator in the critical point of the investigated specimen in which the material structure is damaged (strain localization or fracture). Basically, the ratio of the first invariant of stress tensor and second invariant of stress tensor deviator is taken as the indicator of stress state. In the papers of associates from the Laboratory for metal forming of the Faculty for Technical Sciences in Novi Sad, in the limit formability area at cold forming, the following ratio is taken as the indicator of stress state [1], [2]:

$$\beta = \frac{I_1}{\sqrt{3|I_{D2}|}} = \frac{3\sigma_m}{\sigma_e} \tag{2}$$

where:

I_1 - the first invariant of stress tensor,

I_{D2} - the second invariant of stress tensor deviator,

σ_m - mean hydrostatic pressure,

σ_e - equivalent (effective) stress.

In disproportional (non-monotonous) processes, stress state indicator constantly changes throughout the forming process; therefore it is necessary to introduce mean value of indicator β_{av} [1],[2] [5]:

$$\beta_{av} = \frac{1}{\varphi_e^l} \int_0^{\varphi_e^l} \beta(\varphi_e) d\varphi_e \tag{3}$$

In case that material damage occurs on free surface of the formed piece (plane stress state), indicator of stress state β in critical point of the specimen is determined by the application of forming theory [1], [6] :

$$\beta = -\frac{1+\frac{1+2\alpha}{2+\alpha}}{\sqrt{1-\frac{1+2\alpha}{2+\alpha}+\left(\frac{1+2\alpha}{2+\alpha}\right)^2}} \quad (4)$$

In the given expression, coefficient α is defined by change of strains components in two perpendicular directions: $\alpha = \frac{d\varphi_\theta}{d\varphi_z}$, i.e. by "strain history" $\varphi_\theta = f(\varphi_z)$.

In the case of non-monotonous forming, it is necessary to establish the dependence of stress state indicator on effective strain $\beta = f(\varphi_e)$, and then apply the expression (3) to calculate mean value of this factor.

The paper [4] presents a simpler methodology for determining the mean value of stress state indicator, which gives the results equivalent to the ones obtained by previous methodology and is based on flow theory. The mean value of stress state indicator in that case is determined based on limit values of main strains components:

$$\beta_{av} = \frac{2}{\varphi_e^l}(\varphi_1^l + \varphi_2^l) \quad (5)$$

where:

φ_1^l and φ_2^l - main natural strains in fracture zone

φ_e^l - effective strain in the moment of specimen fracture

Fig. 2 shows the limit forming diagram for steel EN: 100 Cr6, determined by application of basic methods of deformation: uniaxial tension (*β=1*), torsion (*β=0*) and compression (*β=-1*). After that, the data obtained by upsetting the cylinders of different heights (*A, B,C*) by recessed dies was entered into diagram. Lines of „strain history" are drawn in the diagram for particular specimen series: series *A* specimens of dimensions ∅20x35 mm, series *B* specimens of dimensions ∅20x40 mm and series *C* specimens of dimensions ∅20x50 mm. According to Fig. 2, the influence of stress state indicator on limit formability of the material is obvious. Based on that diagram, it can be concluded that lower values of stress state indicator (processes in which compressive stress components dominate) provide higher values of limit strains and vice versa – processes in which tensile stress components dominate result in lower values of limit strain. Because of intensive obstruction of radial material flowing at cylinder upsetting by recessed dies, lower values of limit strain are realized compared with data obtained for cylinder upsetting by flat dies. A slight increase of specimen height leads to increase of limit strain (Fig. 2).

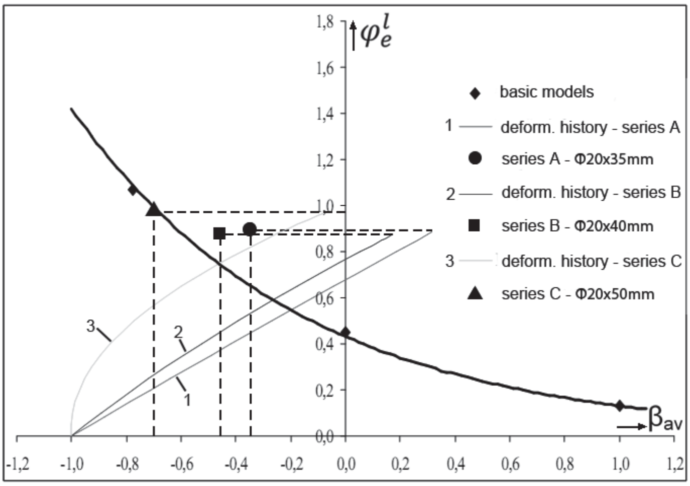

Fig. 2. *FLD for steel 100 Cr6 and strain history at cylinder upsetting with recessed dies [5]*

Strain history and change of β factor during the forming process (Fig. 2) show that the change of stress state and considerable decrease of forming potential occur in compression process. The advanced objective is, definitely, to retain the coefficient β in the area of negative values.

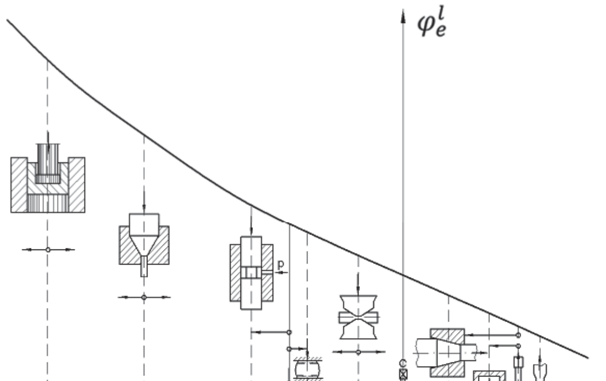

Fig. 3 *FLD based stress formability index and effective strain [6]*

Figure 3 shows the FLD in which the positions of some forming methods are defined based on estimation of stress state indicators. Well-known theoretical solutions for stress components were used in the analysis, based on which stress state indicator β was determined. Vertical broken lines show conditionally that there is proportional forming at investigation, with linear strain history and constant stress state indicator

($\beta = const.$), while horizontal arrows show possible moving of particular processes in FLD conditioned by change of relevant process parameters (contact friction, geometry of tools and specimen etc.).

3. SHEET METAL FORMING

In the area of sheet metal forming by deep drawing, it is best to observe and express the limit formability within the forming space of natural strains. The first forming limit diagrams were formed in the 60-ties, for the needs of the car industry , in order to establish the universal approach for estimation of limit values of strain, independent on stress-strain scheme and geometry of work piece being formed. Forming limit diagram can be formed in various ways, whereat the conditions of proportional forming must be complied with. Figure 4. shows the FLD for low-carbon steel sheet metal, intended for manufacture of passenger car-body parts. FLD was determined by the Nakazima procedure [7]. The left part of the diagram, with the negative second principle line strain, is typical for so called pure deep drawing, and the right part is typical for stretching (both natural main strains are positive). The following factors have the most significant influence on the limit curves position and shape: material (type and thickness) experimental methodology, measuring grid size, strain history.

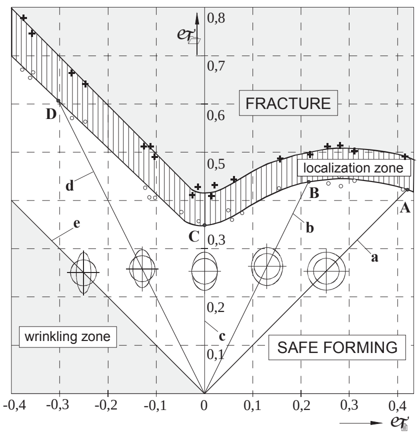

Fig. 4 *Forming Limit Diagram (FLD)*

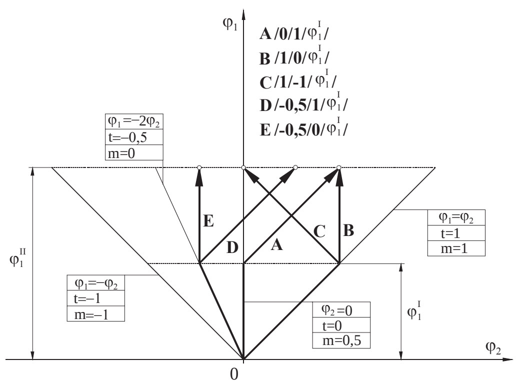

Fig. 5 *Different strain paths at two-phase forming*

Analytical description and understanding of the forming process are rather simple regarding proportional forming. However, the actual processes most often take place in conditions different from proportional forming conditions. This is especially prominent in multi-operational processes of sheet metal forming. The strain path is completely described by strain trajectory- the trajectory of points which are for the corresponding measuring fields into the system of main linear strain $\varphi_1 - \varphi_2$ for each moment of drawing. Figure 5 shows, respectively, the most often used linear strain paths for two-phase process [8].

For plane stress state and proportional forming, or each phase of such forming, the following is valid [8]:

$$t = \varphi_2 / \varphi_1 = const \tag{6}$$

or the coefficient of stress ratio for isotropic material can be applied:

$$m = \frac{\sigma_2}{\sigma_1} = \frac{2\varphi_2 + \varphi_1}{2\varphi_1 + \varphi_2} = \frac{2t+1}{2+t} = const \tag{7}$$

where σ_1 , σ_2 are main stresses on sheet metal plane.

Figure 6 shows FLD forms for various forming histories. The most favourable strain path is, obviously, uniaxial tension in the first phase (t=-0,5) and biaxial tension in the second phase (t=1).

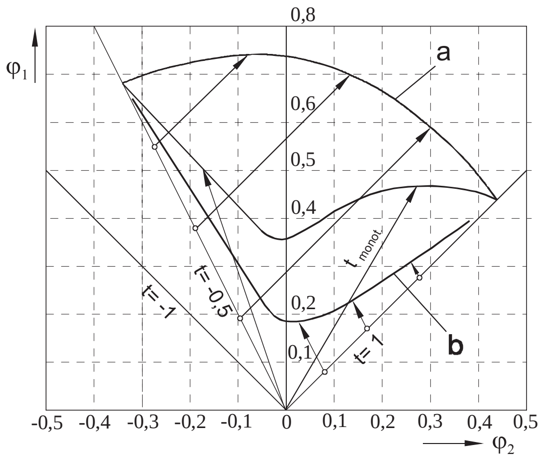

Fig. 6 Complex strain paths and corresponding FLD [7]

In Metal forming laboratory of the Faculty of Mechanical Engineering in Kragujevac, the influence of strain history on limit formability of thin sheet metals has been investigated for many years. In the course of that, standard two-phase investigation schemes were used: the first phase involved the realization of pure uniaxial or complete biaxial tension, and in the second phase very different forming was realized [9].

At forming of sheet metal with dominant negative second strain, such as pure deep drawing, the influence of strain history is more complex. Such procedures integrate very different stress-strain schemes; therefore, the influence of previous forming is not easy to illustrate. The results which are presented further are related to classic, so called pure deep drawing of axis-symmetrical work piece of 50 mm diameter and blank of 100 mm diameter. The results are shown for determining the successful forming fields in the system „blank holding force-drawing depth" at application of various contact conditions (dry surfaces – D, lubrication by oil – O, application of polyethylene foil and oil as lubricants F+O), Fig. 7 [7], [10].

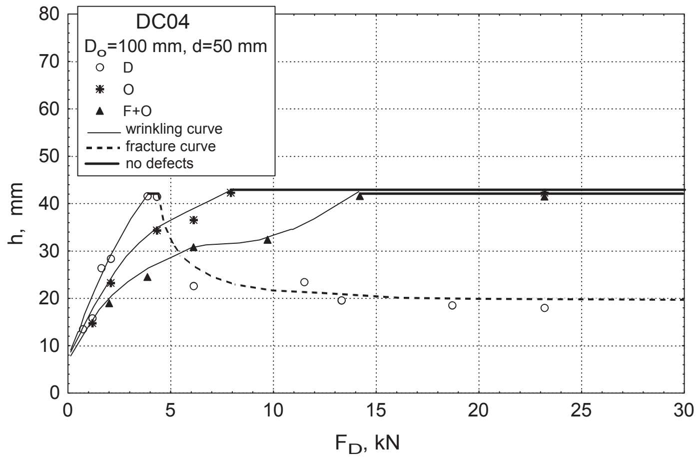

Fig.7 *Dependence of drawing depth on blank holding force for one drawing phase*

Successful forming field is bordered with wrinkle line (full line) on one side and with fracture line (broken line) on the other side. It is obvious that only in case D there are both borders. In other cases, for given drawing ratio, there is no fracture at drawing.

Two-phase strain history was realised as follows: in the first phase, biaxial uniform tension was performed up to the amount $\varphi_1 = \varphi_2 = 0{,}189$, mark „t=1„ trajectories in Figure 6. Then, for the same conditions as previously, drawing was performed and successful forming field was determined, Fig.8.

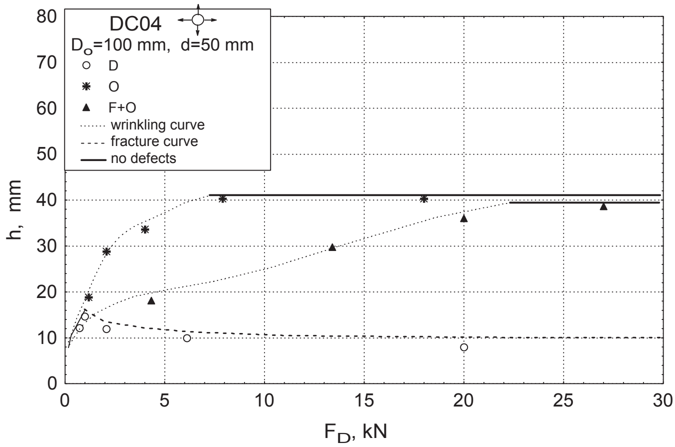

Fig.8 *Dependence of drawing depth on blank holding force for two phase forming*

In case of ideal lubrication, similar ratios were obtained. However, the increase of friction in contact leads to drastic reduction of successful forming field, e.g. the largest depth decreases from 42 mm to 18 mm with the absence of any type of lubrication. Full drawing depth at oil lubrication, at two-phase path, is realized when blank holding force increases considerably, from 18 to 22 kN. Due to reduced sheet metal thickness, total drawing force is smaller.

4. CONCLUSION

Determining of forming limit diagram has practical significance, because it enables the designing of bulk forming process with minimal number of forming operations or phases, which reflects on final work piece quality and increase of economic effects in production. Optimization of the actual technological process with formability criterion requires previous experimental determining of forming limit diagram and detailed analysis of stress-strain state per forming phases. In that sense, it is possible to apply software packages for numerical simulation of bulk deformation process, which should enable defining of the position of actual forming phase in forming limit diagram.

For established and unchangeable forming conditions (material, speed, temperature), the possibility for changing limit strain values is most efficiently influenced by change of stress state.

At experimental determining of formability properties, it is necessary to comply with the condition of so called strain history. This means that limit strain values must be established in conditions which satisfy proportional forming rules.

In sheet metal forming by deep drawing, when determining FLD, proportional forming rules must be complied with. It is reasonable to use FLD in conditions equivalent to the experimental ones. In two-phase strain trajectories, previous uniaxial tension raises the limit strains field in FLD. Thereat, larger local strains are realized, as well as smaller drawing depths.

If FLD is obtained from sheet metal which was previously biaxial tensed, FLD curve moves into the lower strains field and the position of FLD depends considerably on previous strain ratio.

5. LITERATURE

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