INFLUENCE OF STRAIN HISTORY ON LIMIT FORMABILITY IN METAL FORMING

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ABSTRACT

The paper gives definitions and explanations about forming limits for bulk metal forming and sheet 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 biaxial tension-stretching and the area of pure deep drawing of axis-symmetrical pieces.

KEYWORDS: Metal forming, Material formability, 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/:

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

where:

D_M – material formability,

φ_e^l – limit strain,

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

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.

3-5 October 2011,
Thessaloniki, Greece
icmen

Proceedings of the 4th International Conference on Manufacturing Engineering (ICMEN)
Edited by: ***Prof. K.-D. Bouzakis****,*
Director of the Laboratory for Machine Tools and Manufacturing Engineering (EEΔM) of the Aristoteles University Thessaloniki and the Fraunhofer Project Center Coatings in Manufacturing (PCCM), a joint initiative by Fraunhofer-Gesellschaft and Centre for Research and Technology Hellas
Published by: EEΔM and PCCM

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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.

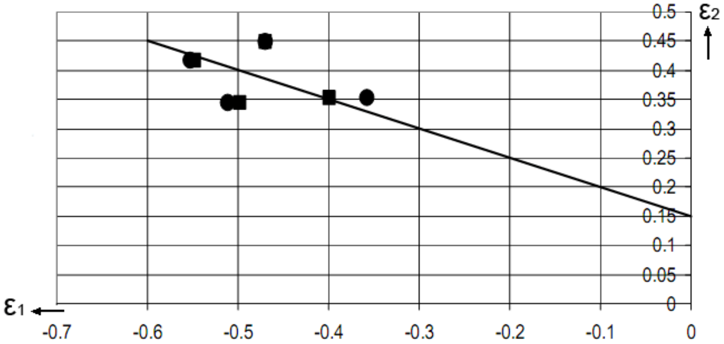


Figure 1: Limit strains curve at compression by conical dies /3/.

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/:

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

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 /2/, /6/:

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

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:

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

where:

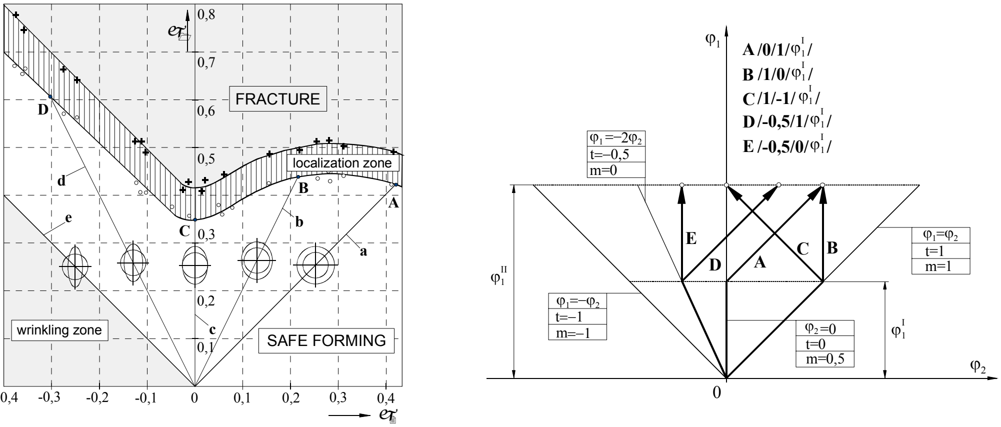
φ_1^l and φ_2^l - main natural strains in fracture zone

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

Figure 2 and Figure 3 shows scheme of process and test specimen, and fig. 4 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 (figure 2) 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 Figure 4, 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

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

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



a) b)

Figure 6: a)Forming Limit Diagram (FLD, b) Different strain paths at two-phase forming.

The following expression is valid for anisotropic material:

$$m = \frac{(\frac{1}{r_0} + 1)t + 1}{\frac{1}{r_{90}} + t + 1} \tag{8}$$

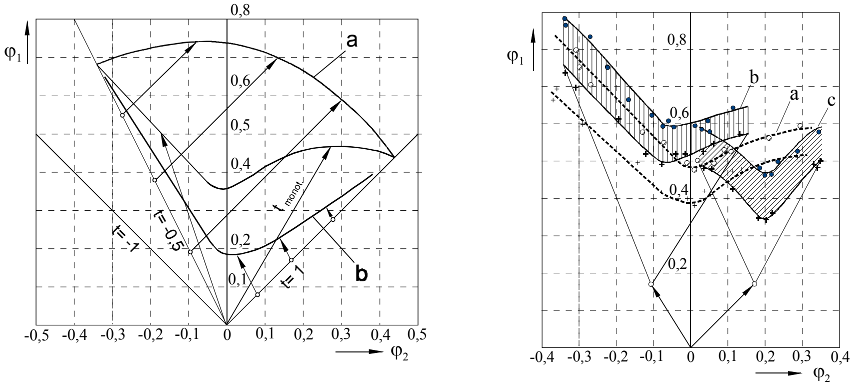
where: r_0, r_{90}, are the normal anisotropy coefficients in directions 0^0 and 90^0 in relation to the rolling direction.

Figure 7a 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). Corresponding FLD is marked as b in figure 7b. 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. The results for two typical forming cases – stretching and pure deep drawing – will be presented.

3.1. Stretching

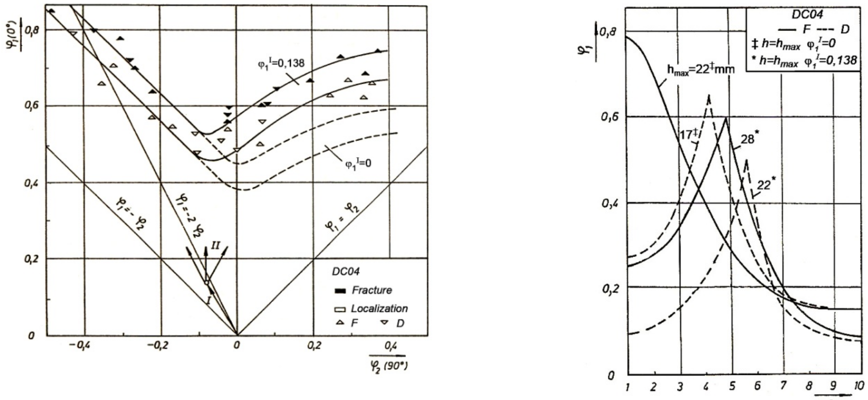
Figure 8a. shows the experimentally determined FLD for uniaxial proportional (φ_1^I= 0) and two-phase stretching. Mark F is related to the application of polyethylene foil as lubricant, and mark D- to dry contact surfaces. Punch diameter is 50 mm and blank diameter is 120 mm, whereat flange moving is blocked during investigation. Material DC04 was used, which is intended for deep drawing of car body parts.

The first phase involved uniaxial tension of the band which would be stretched subsequently (φ_1^I=0,138). The obtained results comply with previous conclusions: tension first, and then stretching, raise FLD curve, but at the expense of macro-geometry, which results in realization of higher limit strain ratios with smaller fracture depth /9/. With such strain history, the results are obtained which are completely incompatible with the results of typical sheet metal stretching investigations: larger fracture depth matches smaller limit strain and vice versa, figure 8b. In such conditions, the influence of contact friction is extremely prominent, which is observed based on principle strains distribution, figure 8b. Marks of measuring grid circles, through which the strains are determined, are denoted on the abscissa.



a) b)

Figure 7: a).Complex strain paths and b) FLD display: a - single-phase, corresponding FLD /7/ proportionally, b - two-phase, first phase uniaxial tension, c - two-phase, first phase biaxial tension.



a) b)

Figure 8: a) One and two-phase strain path FLD, b) Natural strain distribution at fracture for one and two-phase strain path.

At two-phase forming, proportionality conditions are nearly satisfied, according to the expression (7), in view of approximate linearity of strain paths in points where fracture occurs. For example, point c=1 matches the top of the work piece being stretched – uniaxially, in the first phase, and then biaxially until occurrence of fracture, Figure 9.

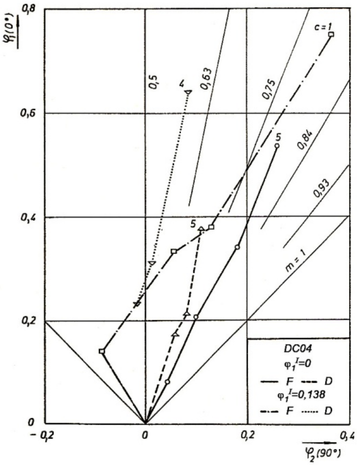
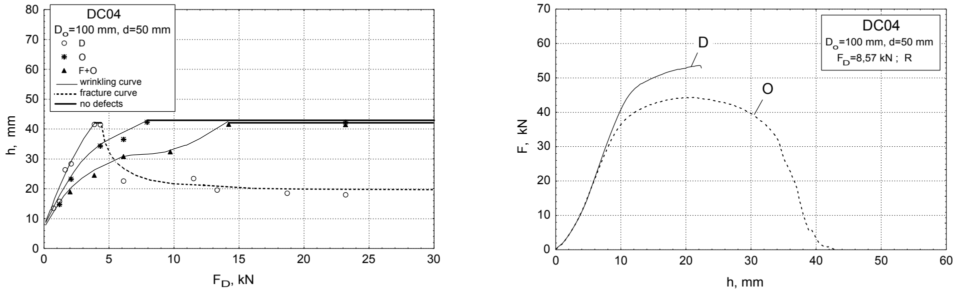


Figure 9: Strain path at one and phase stretching.

3.2. Pure deep drawing

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), Figure 10a,. In addition to that, dependencies of drawing force in the function of punch displacement are shown as well, figure 10b. /7/,10/.

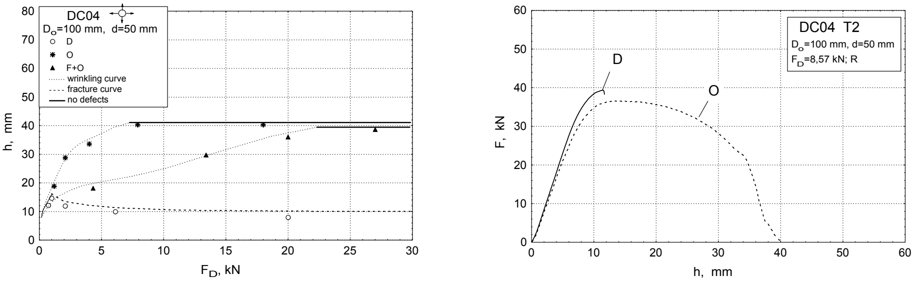


a) b)

Figure 10: a) Dependence of drawing depth on blank holding force for one drawing phase, b) Punch load vs. displacement for single-phase drawing.

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 7a. Then, for the same conditions as previously, drawing was performed and successful forming field was determined, Figure 11a.



a) b)

Figure 11: a) Dependence of drawing depth on blank holding force for two phase forming, b) Punch load vs. displacement 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. The obtained results are in compliance with ratios in figure 7b, considering the fact that previous biaxial tension leads to lowering of limit strains curve in FLD.

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. ACKNOWLEDGEMENT

This paper is a part of the investigation within the project TR 34002 financed by Serbian Ministry of Science and Technological Development.

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