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EXPERIMENTAL VERIFICATION OF DIFFERENT THEORETICAL APPROACHES FOR DEFINING FLD

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Abstract: Workability of materials is the possibility of permanent changes in shape and dimensions of workpieces without cracking or other forms of damage to the structure. This property, which numerically valorized by size of limit effective strain, depends on type of material, the initial structure and processing conditions. This paper shows results related to the defining of FLD in bulk metal forming processes, based on theapplication of various theoretical approaches for determining of mean values of ß – factor and strainlimit.
Keywords: workability, ß-factor, strainlimit, FLD, cold upsetting

1. INTRODUCTION

Key term in the area of forming and use of metal materials through which relations between behavior of materials within forming system, process parameters and external conditions during plastic forming process is formability. Although formability has been understood and interpreted in various ways in the past, it has also been often brought in relation with plasticity, it seems that the most complete definition was provided by Kolmogorov [1], according to which formability of material is ability to change shape permanently under certain conditions without occurrence of cracks, deformation localization or other type of damage to the surface i.e. internal structure of the specimen. Formability depends on large number of factors which can generally be divided into two groups: factors of the material and factors of forming conditions [2-4]. Implicit shape of this function is represented with the expression (1):

$$F_M \equiv \varphi_e^l = f\left(H, S, T, \dot{\varphi}, T_\sigma \ldots\right) \tag{1}$$

Indicator of formability can be any variable which can quantitatively describe degree of damage to the material structure under certain forming conditions [3]. Nonetheless, it is generally accepted that numerical indicator of material formability is value of effective strain limit in the forming critical zone at the exact moment crack occurs.

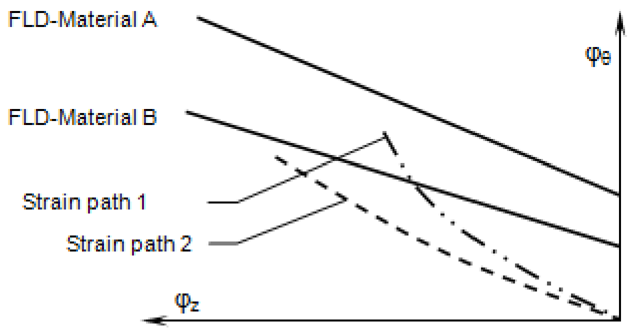


Figure 1. FLD scheme for bulk forming processes - $\phi_\theta = f(\phi_z)$ [3]

Graphical interpretation of equation (1) is forming limit diagram (FLD), and its definition can be based on different methodologies. Basically, there are two methodologies in determining FLD in the processes of bulk forming. The first one relates to determination of forming limit curve as a function of main strains $\phi_\theta = f(\phi_z)$, at the exact moment of material destruction (Figure 1).

The above presented methodology of determining FLD for various processes and forming conditions can be found in large number of papers. Hartley and associates [5] have been researching limit formability in the process of cold upsetting of cylindrical specimens with cone plates. In the papers [6-7] are presented the resultsof numerical and experimental determining of limit formability for the process of upsetting of cylindrical specimens with vertical surface defects. Investigating the influence of nucleation and growth of micro-voidson the inclusions from the aspect of limit possibilities of upsetting cylindrical specimens, for the purpose of defining FLD Ragab [8] has used the identical methodology. The same approach to defining FLD has been noted in other authors [9-12].

The second methodological approach used in determining FLD is based on establishing direct dependence of effective strain limit ϕ_e^l to generated stress state in the critical zone of forming. Influence of stress state to limit formability is valorized through indicator of stress state ß which is defined by relation of invariants of stress tensor:

$$\beta = \frac{I_1}{\sqrt{3}\ \left|J_2\right|} = \frac{3\sigma_m}{\sigma_e} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\frac{\sqrt{2}}{2}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}} \qquad (2)$$

In paper [13] Kolmogorov has chronologically presented technological advancements that have enabled development and improvement of methodologies for defining FLD, based on direct connection of strain limit and stress state ϕ_e^l= f(ß).

In paper [14], Abdel-Rahman presents relatively reliable approach for FLD approximation using only two mechanical tests (uniaxial tension and uniaxial upsetting). Functional dependence between effective strain $\phi_e$and stress state indicator β has linear character.

But, according to this methodology, basic shape of forming limit curve is defined using three basic (monotonous) forming models (uniaxial tension ß = +1, torsion and uniaxial cylinder upsetting ß = -1) figure 2.

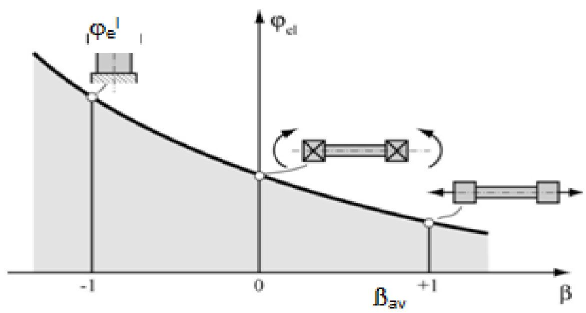


Figure 2. FLD - ϕ_e^l= f (ß) – basic forming models [2, 4]

Such concept allows relatively simple and reliable way to identify stress-strain state in the zone of critical material damage, in other words to determine three points of FLD. Defining the FLD in more detail is achieved by application of new forming models. However, since those are mainly non-monotonous, dominant processes of plastic forming, when determining the abscise coordinate in FLD it is necessary to calculate average value of ß-factor.

Aim of research presented in this paper is quantitative determination of level of agreement regarding values of average values of stress state indicators ($ß_{av}$) and strain limits (ϕ_e^l) while using different theoretical approaches for their determination. Experimental research data obtained in processes of upsetting cylindrical andtapered specimens with flat plates was used for realization of the above mentioned aim. Also, one of the aims of research was to, through defining FLD identify limit abilities of forming steel C45E under conditions of normalized initial micro-structure state.

2. THEORETICAL ASPECTS OF FLD DEFINING METHODOLOGY

Locating exact place cracks occur is the first activity in analysis of tested material's formability. In the processes of free upsetting occurrence of cracks is common characteristic of free surfaces of the specimen. Actually, cross-section of equatorial plane of the specimen and free surface is forming zone where critical damage of material's structure occurs.

2.1. Identification of stress-strain state in the process of free upsetting

Taking into consideration the fact that during the process of free upsetting radial component of stress does not occur on free surfaces of the specimen, and that friction mechanisms are also not present due to inability to maintain contact with the tool, identification of stress-strain state in the area of critical damage of the specimen is made much easier.

Stress components at the place cracks occur are defined with equations (3 and 4) [4]:

$$\sigma_z = \pm\sigma_e \left[1 \quad \left(\frac{1+2\alpha}{2+\alpha}\right) + \left(\frac{1+2\alpha}{2+\alpha}\right)^2\right]^{\frac{1}{2}} \tag{3}$$

$$\sigma_\theta = \sigma_z \left(\frac{1+2\alpha}{2+\alpha}\right) \tag{4}$$

Previous equations enable defining stress state indicators *ß* in the following form where:

$$\beta = \frac{\sigma_r + \sigma_\theta + \sigma_z}{\sigma_e} = \frac{1 + \frac{1+2\alpha}{2+\alpha}}{\sqrt{1 \quad \frac{1+2\alpha}{2+\alpha} + \left(\frac{1+2\alpha}{2+\alpha}\right)^2}} \tag{5}$$

σ_r, σ_θ and σ_z – are components of principal stresses in the directions of axis *r*, θ and *z*,

σ_e– is effective stress

Coefficient α is relation of strain increases (6):

$$\alpha = \frac{d\varphi_\theta}{d\varphi_z} \tag{6}$$

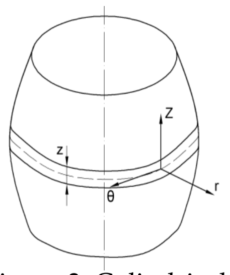


Figure 3. Cylindrical specimen after forming

For application of previous equation it is necessary to determine strain path, $\phi_\theta = f\ (\phi_z)$. In this paper, the elation we were looking for is defined with second degree polynomial:

$$\varphi_\theta = f(\varphi_z) = A\varphi_z + B\varphi_z^2 \tag{7}$$

where: *A* and *B* are coefficients of approximated function.

Components of principal strains ϕ_z,ϕ_θ and ϕ_r in the critical zone of the specimen are determined according to level of marked area Z (Figure 3) and radius of specimen in equatorial plane using non-compressibility condition:

$$\varphi_z = ln\frac{Z_i}{Z_0}, \quad \varphi_\theta = ln\frac{D_i}{D_0}, \quad \varphi_r = -(\varphi_z + \varphi_\theta) \tag{8}$$

where: Z_0, D_0 – are initial values of marked area level and specimen radius, Z_i , D_i – are values of marked area level and radius after *i*phases of upsetting.

Effective strain at the place the crack occurs is determined according to the following pattern (9):

$$\varphi_e = \frac{\sqrt{2}}{3}\sqrt{(\varphi_z - \varphi_\theta)^2 + (\varphi_\theta - \varphi_r)^2 + (\varphi_r - \varphi_z)^2} \tag{9}$$

2.2. Forming history

Forming history is dependence of effective strain from stress state indicators ϕ_e=f(Tσ)=f(ß). Under monotonous forming conditions (basic models) variations of ß-factor do not occur. However, in non-monotonous processes, changes of stress state during plastic forming have to be identified and taken into consideration while defining FLD because it has been determined that amount of damage to microstructure is proportional to achieved level of forming and its intensity depends on stress state [1]. For those reasons, when defining FLD we use average value of stress state indicator ß. Equations for determining $ß_{av}$ and they depend on theoretical approach used for their defining. According to deformation theory it can be determined using equations (10),[2]:

$$\beta_{av} = \frac{1}{\varphi_e^l}\int_0^{\varphi_e^l} \beta(\varphi_e)d\varphi_e \tag{10}$$

If critical damage to the material is generated on the free surface of the specimen, like in free upsetting processes, we used methodology based on flowtheory[2, 15-17] for determining $ß_{av}$. In this case *ß*-factor is determined according to strainlimit values:

$$\beta_{av} = \frac{2}{\varphi_e^g}\,(\varphi_1^l + \varphi_2^l\,) \tag{11}$$

where: $\phi_1$and ϕ_2 – are components ofprincipal logarithm strains in the zone cracks occur, ϕ_e^l– is effective strain in the moment of specimen destruction.

Effective strain limit is determined by numerical integration (12):

$$\varphi_e^l = \frac{2}{\sqrt{3}}\int_0^{\varphi_z^l}\left[1 + A + 2B\varphi_z + (A + 2B\varphi_z)^2\right]^{1/2} d\varphi_z \qquad (12)$$

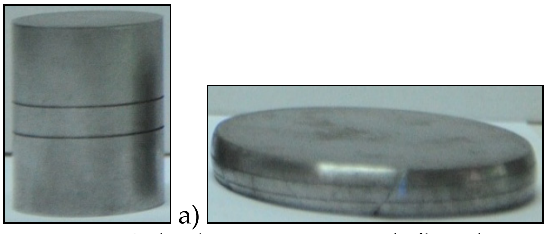
Experimental verification of previously explained approach, for different materials, is verified in papers by Alexandrov and Vilotić[15-17].

3. EXPERIMENTAL RESEARCH

Experimental research was realized in two phases. In the first phase we used basic forming models for defining FLD for steel C45E. The second phase deals with research of limit formability of normalized taperedspecimens in the process of upsetting with flat plates.

3.1. Basic forming models

Upsetting of cylindrical specimens with flat plates was realized incrementally until the cracks occurred at the free surface. For experimental purposes we used specimens with initial dimensions Ø20x25 mm (Figure 4a). Identification of strain state at the place critical damage of microstructure occurs was performed by application of equation (8), and regressive analysis enabled determination of principal strain dependence $\varphi_\theta = f(\varphi_z)$at the place crack occurred using second degree polynomial, respecting limiting condition that in the beginning of upsetting process $\varphi_\theta=\varphi_z=0$:



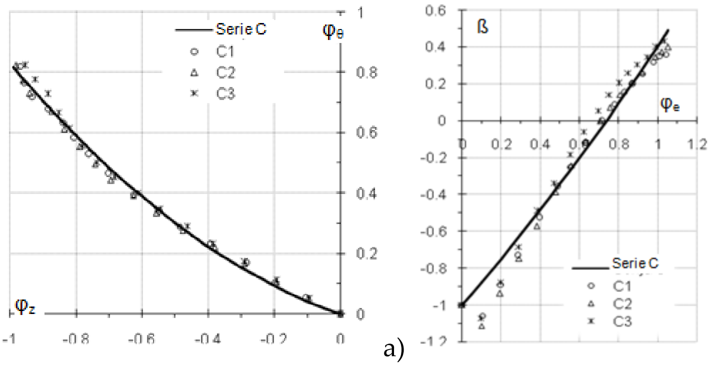
a) b)

Figure 4. Cylinder upsetting with flat plates: a) initial specimen, b) formed specimen

$$\varphi_\theta = -0.3718\,\varphi_z + 0.4574\,\varphi_z^2 \qquad (13)$$

Graphical interpretation of previous equation with individual experimental points (φ_θ, φ_z) is shown on Figure 5a. Using approximate function (13) and pattern (5) values of stress state indicators were determined according to upsetting phases, in other words according to forming history expressed as second degree polynomial. (Figure 5b):

$$\beta = 0.1803\,\varphi_e^2 + 1.2234\,\varphi_e - 1 \qquad (14)$$



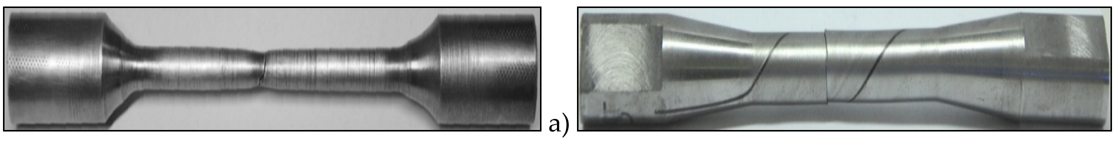
a) b)

Figure 5: Upsetting of cylinders with flat plates: a) strain path; b) forming history

Uniaxial tension and torsion tests were realized under monotonous forming conditions. After processing experimental results we obtained following results:

- Uniaxial tension ß=+1 ϕ_e^g= 0.0780
- Torsion ß=0 ϕ_e^g= 0.6212

In Figure 6 are photographs of test pieces formed in processes of uniaxial tension and torsion.



a) b)

Figure 6. Formed test pieces: a) uniaxial tension; b) torsion

3.2. Upsetting of tapered specimen with flat plates

For fuller characterization of steel C45E formability we created a model of upsetting of tapered specimen with flat plates. Initial shape and dimensions of this new model (Figure 7a) were defined in a manner that they provide dominant impact of tension components of stress to development of damage to the structure and occurrence of cracks.

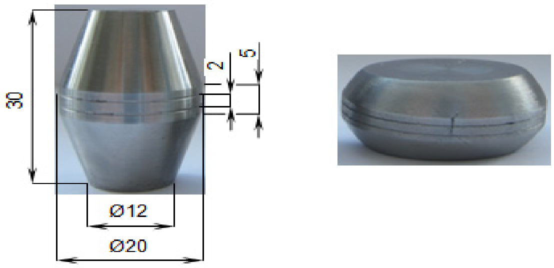


Figure 7. Upsetting of tapered specimen with flat plates: a) initial specimen; b) formed specimen

Realization of the experiment and processing of experimental results for upsetting tapered specimen wit flat plates was conducted in the same manner as in the process of upsetting cylindrical specimens. Graphical image of strain path (15) and forming history (16) was provided on Figure 8.

$$\varphi_\theta = -0.3360\,\varphi_z + 2.5986\,\varphi_z^2 \quad (15)$$

$$\beta = -9.4133\,\varphi_e^2 + 8.8553\,\varphi_e - 1 \quad (16)$$

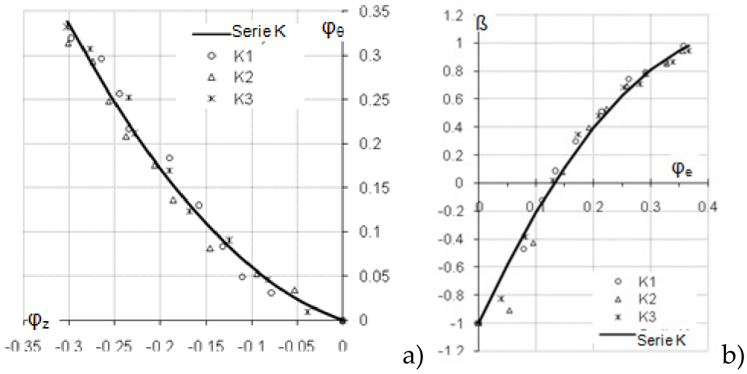


Figure 8. Upsetting of tapered specimen with flat plates: a) strain path; b) forming history

3.3. Average values of stress state indicators and strain limit

Average values of ß-factor for the processes of upsetting cylindrical and tapered specimen, according to theoretical approaches, were determined using equations (10) and (11). Effective strain limit was calculated using limit values of individual forming components (equation 9), or numerical integration of equation (12). Results are provided in Table 1.

Table 1. Comparison of values $ß_{av}$ and ϕ_e^l

Upsetting of cylindrical specimen					Upsetting of tapered specimen				
N_0	Deformation theory		Flow theory		N_0	Deformation theory		Flow theory	
	$ß_{av}$	ϕ_e^l	$ß_{av}$	ϕ_e^l		$ß_{av}$	ϕ_e^l	$ß_{av}$	ϕ_e^l
C1	-0.3167	1.0421	-0.2770	1.0584	K1	0.2041	0.3565	0.2030	0.3943
C2	-0.3090	1.0539	-0.2966	1.0801	K2	0.1445	0.3556	0.1633	0.3889
C3	-0.2649	1.0341	-0.2371	1.0469	K3	0.2073	0.3668	0.1780	0.3963
Serie C	-0.2963	1.0434	-0.2707	1.0601	Serie K	0.1862	0.3595	0.1851	0.3919

3.4. Forming limit diagram for steel C45E

According to presented experimental and numerical data, we defined FLD for steel C45E. In Figure 9 is provided comparison of forming limit curves depending on theoretical approach applied while determining $ß_{av}$ and ϕ_e^l. Research results for individual specimens were presented through mean values of series for tested forming models.

4. CONCLUSION

While analyzing different approaches to determining FLD we can draw a conclusion that both of them are basically focused on establishing functional dependence between strain limits and stress state in the critical zone of material's structure damage. Using the dependence $\phi_\theta = f(\phi_z)$ indirectly. FLD constructed in such manner can be applied only to models and conditions under which it was constructed.

Direct linking of strain limits to stress state in the forming zone through stress state indicators is provided with the relation $\phi_e^l = f(\beta)$, which is more general manner of defining FLD. Such approach enables more comprehensive insight to the complex area of limit formability of materials taking into consideration forming conditions.

Results of experimental research have confirmed high level of agreement in terms of numerical values of $ß_{av}$-factor and strainlimit ϕ_e^l, regardless to theoretical approach used for their determination. Differences are result of lack of adequate measuring equipment for identification of forming state during experimental research. From the practical standpoint, determining $ß_{av}$ and ϕ_e^l using flow theory is more acceptable, compared to the approach based on deformationtheory because it does not require iidentification of stress state, which is very significant under non-monotonous forming conditions. Besides that, such approach provides that certain conditions are not controlled during experimental research (in example, contact friction).

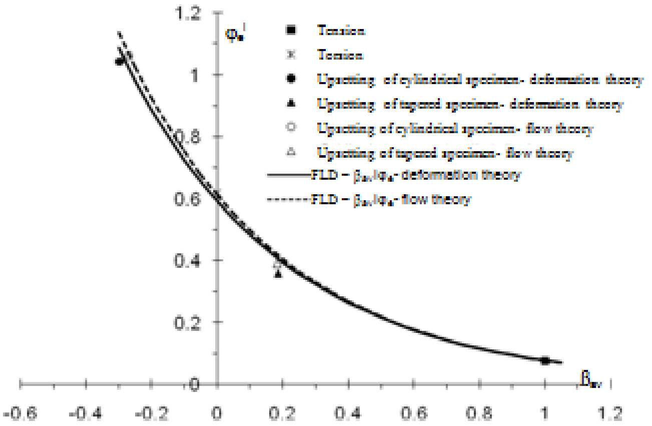


Figure 9. FLD for steel C45E-comparison for determinatio of $ß_{av}$ and ϕ_e^l using different theoretical approaches

However, in case of re-designing technological procedure of metal component production, non-identifying history of forming process can lead to wrong judgement and wrong solutions. For that reason we can draw a general conclusion that following the changes in stress state in the zone critical damage occurs provides more complete and more reliable analysis of limit formability.

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