INFLUENCE OF CONTACT CONDITIONS AND STRAIN PATH ON STRETCHING OF STEEL AND AL-ALLOY SHEET METALS

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ABSTRACT

Biaxial tension – stretching of sheet metals is one of characteristic stress-strain-schemes, which in the course of sheet metal forming by deep drawing may exist in particular work piece zones or may dominate completely (Erichsen's test). In such forming conditions, tribological conditions of tool and sheet metal contact are extremely important. In addition to fracture depth, which is a main investigation indicator, the paper also presents more complex parameters for estimation of contact conditions influence – fracture force and realized strains distribution, as well as relations in forming limit diagram. Furthermore, it shows that in the multistage forming conditions, i.e. at modification of so called strain paths, contact conditions have a considerable influence on the degree of realized limit strains. Steel and Al-alloys sheet metals were used in the experiment. In addition to the analysis from the formability aspect, the specified methodology can be used with great success for the estimation of technological qualities of lubricants for deep drawing.

KEYWORDS: Deep drawing, Stretching, Formability, Friction, Strain

1. INTRODUCTION

In deep drawing of complex geometry parts, such as vehicle body elements, various stress-strain schemes may exist in particular zones of the workpiece being formed, with tribological conditions influence which might often be complex. On work piece flange, next to pure tangential compression zone, parts without completely curved inner contour have uniaxial tension, which moves to bending field on the die edge. If there are draw beads on the flange, stress scheme gets complicated significantly. As a rule, uniaxial tension is dominant in the wall of the work piece which conveys the forming force. In the specified zones, it is necessary to reduce friction, i.e. to control friction on flange, in order to control sheet metal moving into die opening. During the last few years, researchers have given great attention to the control of blank holding force on the flange of the work piece being drawn in the real time /1/. From the aspect of successful forming, i.e. utilization of formability potential of the material being formed, the zone under the punch face, where stress scheme of biaxial tension is dominant, is extremely important.

The influence of tribological factors in deep drawing process is as important as the influence of other main process factors – machine, tools and work piece material /2/. By using appropriate combination of specified factors, it is possible to realize reliable production and obtain high-quality piece.

In physical modelling of deep drawing process, i.e. modelling of contact friction influence, it is necessary to comply with similarities of stress-strain ratios, as well as similarities of main tribological parameters: speed, pressure and temperature on sliding surfaces. Figure 1 shows, in details, the tribo-model of stretching in global survey of other models significant for deep drawing. Basic tribo-models are: sliding between flat surfaces, bending with tension and sliding across the draw bead (strip draw tests) and complex tribo-models of stretching and pure deep drawing /3/.

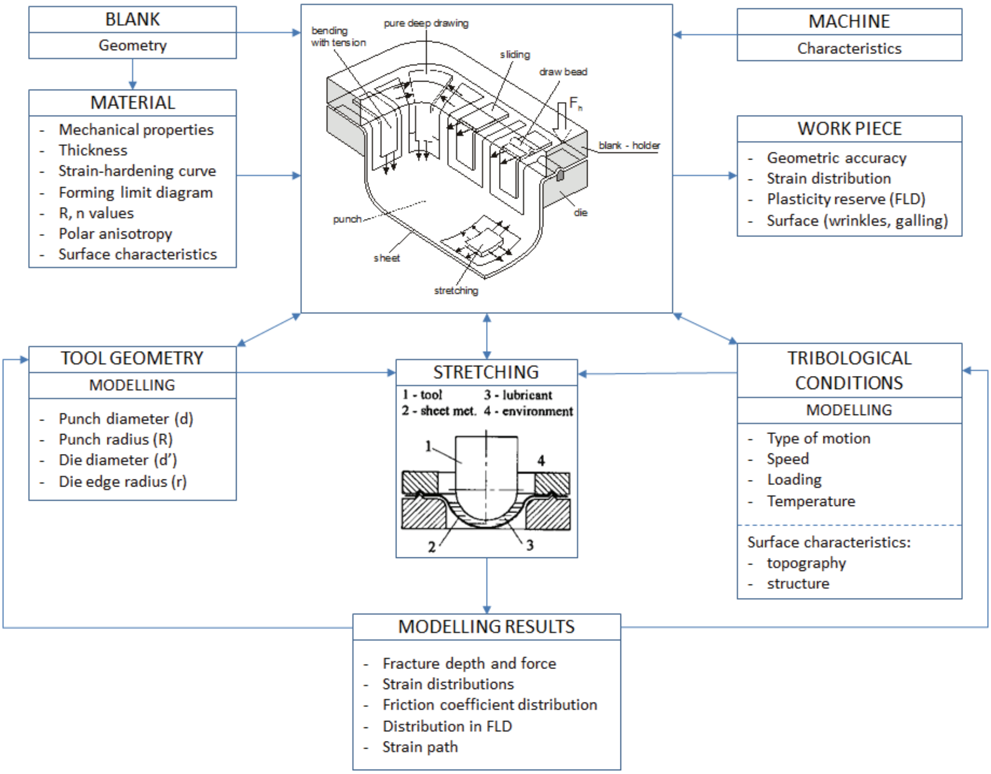

Figure 1: Tribo model of stretching in global scheme of tribo-modelling of deep drawing /3/

In general, with such approach, the following can be observed: local zone of the work piece being formed, several local zones and a complete work piece. Numerical modelling enables integral analysis of all individual work piece zones.

According to the size of the examined work piece zones and characteristics of the measuring parameters, the results of tribological research can be divided into three groups /4/: physical indicators (friction coefficient, friction force, sliding distance etc.), macro indicators for the whole work piece (force and depth of drawing, limiting drawing ratio etc.) and indicators of strain analysis with limit formability elements (strain distribution, position in forming limit diagram – FLD etc.) for particular zones or whole work piece.

The results which will be presented in the paper are related to so called outer indicators of stretching modelling (which include force and largest depth), as well as to complex indicators of strain. Because of monitoring of so called strain path, it is convenient to monitor the change of strain distribution in particular forming phases, until the appearance of fracture (e.g. comparisons at same depths).

2. CHARACTERICS OF STRETCHING

In deep drawing, the critical section of work piece, which conveys forming force, is located directly above punch radius; therefore, from the aspect of strain localization, it is necessary to have the carrying surface reduction take place as slowly as possible. That is provided due to a higher coefficient of normal anisotropy. Friction on the punch radius should be increased, in this case.

However, at forming by full biaxial tension, work piece flange is blocked, so the strain occurs only in die opening. In order to achieve higher strain ratios, friction in contact of sheet metal and punch should be reduced as much as possible. Stretching of sheet metal is a typical stress-strain scheme characterized by positive values of principal normal stresses, one contact surface between the sheet metal and the tool, and relatively small sliding speed in that zone. In laboratory conditions the stretching has been used for years in the evaluation of the sheet metal formability for deep drawing (Erichsen's test, Olsen' s test).

In the course of stretching, the friction between the punch and the sheet metal must be as small as possible, in order to achieve uniform forming, and smaller degree in particular depth, that is a bigger degree of maximal strain in the course of fracture. Smaller friction corresponds to smaller forming force in identical work piece geometries. Medium friction coefficient has higher values than in pure deep drawing. In the point where new sheet metal zones make contact in the course of lubrication, the oil film is formed and it can remain stable or be disturbed, depending on conditions of contact surfaces /3,5/. Considering the relatively low values of surface pressure, in conditions of boundary lubrication, the adhesive chemical qualities are more important than rheological qualities of a lubricant.

3. EXPERIMENTAL INVESTIGATIONS

3.1. Materials properties

Experimental investigations, the results of which are presented in further text, were conducted under the following conditions: materials were the low carbon killed steel sheet metal (DC04-aluminium killed drawing quality) and Al-alloy sheet metal (AlMg4,5Mn-series 5000). Sheet metal thickness was 0,8 mm.

Application of Al-alloys for the manufacture of some parts of sheathing or complete vehicle body with the aim of reducing vehicle weight, i.e. reducing fuel consumption, has become one of the developmental trends of the leading world car producers. For vehicle body parts, three groups of Al-alloys are most often used: Al-Cu alloys (series 2000), Al-Mg-Si alloys (series 6000) and Al-Mg alloys (series 5000) /6/.

The main properties of Al-alloy are: considerably lower yield strength and tensile strength in comparison with steel, their elasticity module has three times smaller value than steel, elongation, particularly local one, is small, non-homogenous forming is present, normal anisotropy ratio is small (below 1), they are relatively soft and surface can easily be damaged, they can have various forms in dependence on both the method by which they were obtained and applied heat treatment. Mechanical properties and formability parameters of the investigated materials are given in Table 1 and Table 2. Differences between these materials are obvious.

R_p, MPa	R_m, MPa	A_{80}, %	n	r
148	271	21	0,26	0,715
Flow curve (0°) : $K = 152,9 + 305,9\,\varphi^{0,312}$, MPa				

Table 1: Properties of Al-alloy sheet metal.

R_p, MPa	R_m, MPa	A_{80}, %	n	r
179,9	314,6	36,06	0,235	1,51
Flow curve (0^o) : $K = 177 + 388{,}29\,\varphi^{0{,}448}$, MPa				

Table 2: Properties of steel sheet metal.

Figure 2 shows forming limit diagram for steel and various Al alloys which are used for deep drawing /6/.

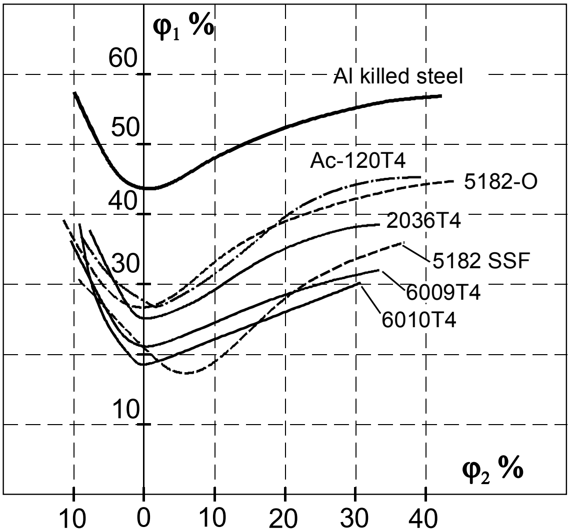

Figure 2: Forming limit diagram for steel and Al-alloys /6/

3.2. Experimental results

All the experiments have been carried out on the universal device for sheet metals investigation – Erichsen 142/12. Principle strain distribution was determined graphometrically, by measuring the deformed elements of the circular grid made of circles of nominal diameter of 3 mm. Measuring were performed optically. Semi-spherical punch diameter was d=50 mm; diameter of blank, fully blocked on flange, was 120 mm. Principal logarithmic strains were marked with φ_1 and φ_2.

Lubrication conditions provided limit condition: technically dry contact surfaces (D) and "quasi-hydrodynamic" lubrication due to the use of polyethylene foil (F). The punch speed was 3.33 $\times 10^{-4}$ m/s. Forming of previously non-deformed sheet metal was marked with $\varphi_1^I = 0$. Variable of strain history has been realized as a two-phase: single-axis tension, in the first phase and stretching in the second phase, marked with $\varphi_1^I \neq 0$, i.e. $\varphi_1^I = 0{,}138$ for steel and $\varphi_1^I = 0{,}05$ for Al-alloy.

Change of drawing force for various lubrication conditions is shown in Figure 3, Figure 4 and Figure 5. It is obvious that the significant differences in realized forces and depths are related to conditions D and F, which was expected. It should be mentioned that with the increase of punch diameter and the inclusion of larger quantities of material in forming process these differences became bigger /3/.

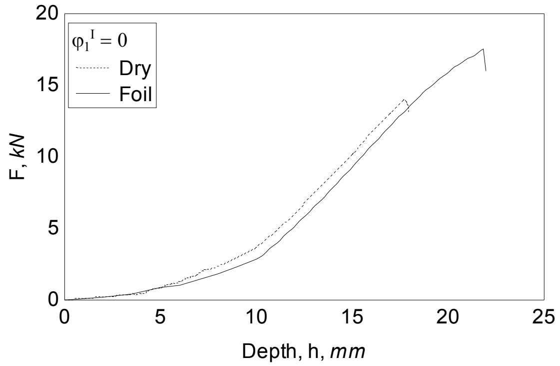

Figure 3: Dependence of force on punch travel for Al and $\varphi_1^I = 0$

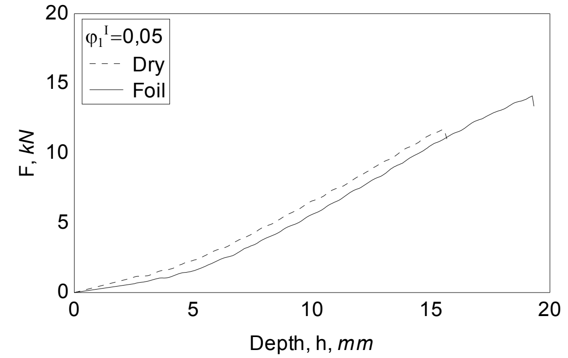

Figure 4: Dependence of force on punch travel for Al and $\varphi_1^I = 0.05$

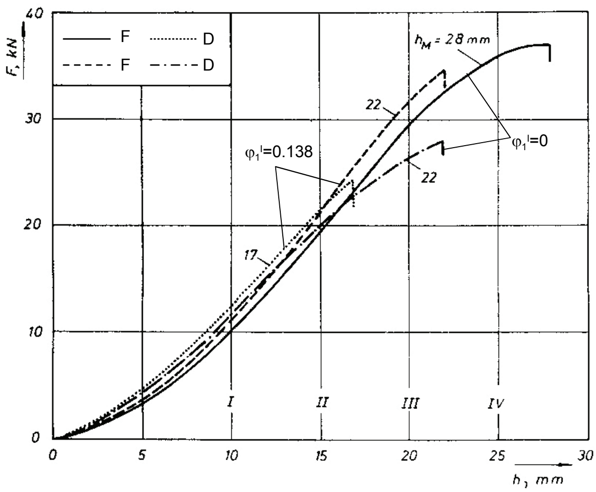

Figure 5: Dependence of force on punch travel for steel and $\varphi_1^I = 0$ and $\varphi_1^I = 0.138$ /7/

Better lubrication is consistent with larger fracture depths and higher forming forces. Due to rather small speed of sliding in contact and high local pressures, materials behaviour in forming is considerably different from the one on flange (higher speed, longer sliding paths). At the same depths, friction reduction leads to smaller forming forces. For specimens, which are formed in two phases, smaller fracture depths occur as the consequence of reduced sheet metal thickness.

If the previous indicators – force and fracture depth can be accepted as ˝outer˝ indicators, realized strain fields, i.e. strain distributions, describe material behaviour at forming in a basic, ˝inner˝ way. In the following figures, characteristic principal strain distributions in meridional section are shown, where point 1 equals the field on the top of formed semi-sphere. Field 10 coincides with die edge. Presented distributions are related to various realized depths and the maximal one, which is consistent with fracture, at limit conditions in contact. Better lubrication moves the fracture point towards workpiece centre, making the distribution more uniform, Figure 6 and Figure 7.

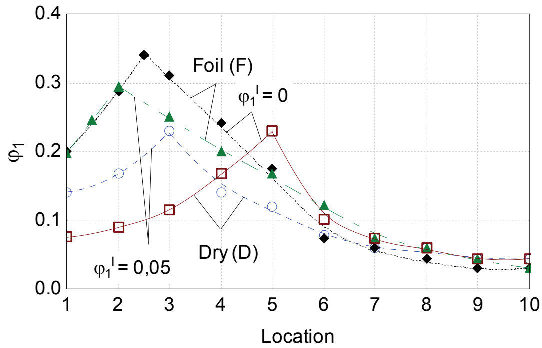

Figure 6: Strain distribution for Al

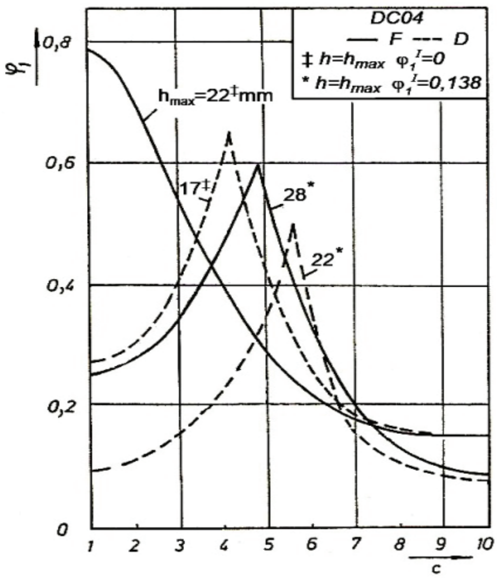

Figure 7: Strain distribution for steel and $\varphi_1^I = 0$ and $\varphi_1^I = 0.138$ /7/

In investigations of Al-alloy, forming was performed for three depths: h_I=8 mm, h_{II}=13 mm and h_{max} at which specimen fracture occurred. Fracture took place at depths (case $\varphi_1^I = 0$): $h_{max(D)}$=17,5 mm, $h_{max(F)}$=21,8 mm. As expected, for steel sheet metal higher values of larger depths were realized: $h_{max(F)}$=28 mm $h_{max(D)}$=22 mm.

In the case of proportional forming, strain trajectories in particular measuring points in principal linear strains space are approximately straight lines /7/. Trajectories are obtained on the principal linear strains surface by inserting the true strain values in the same points for particular forming phases (depth h changes to h $_{max}$). However, the key differences in forming character occur when the principal strains directions change in the course of forming. Due to the complex character of physical and metallurgical appearances inside the material structure, in such forming conditions, the important material formability properties can be obtained by applying the exact experimental procedures for strain fields determining and analysis of forming limit diagram.

Experimental realization of unproportional forming was realized by two-phase procedure; in the first phase, the stripe out of which blank was obtained was subjected to uniaxial tension up to the amount φ_1^I = 0,138 for steel, i.e. φ_1^I = 0,05 for Al, and then stretching was performed until particular depths and the largest depth were obtained. Since such a procedure satisfied the proportional forming conditions in each individual phase, conditions included by localized forming theory in the area of positive second principal strain were fulfilled.

In the course of reliable assessment of realized strain distributions, in addition to the largest – principal strain, it is necessary to take into consideration the second linear strain. Such considerations and analyses are performed in the coordinate system of principal linear strains, although the values on so called forming limit diagram are taken as general limitations in forming. FLD, known as Keeler-Goodwin's diagram, has become a basis for the analysis of formability at deep drawing of thin sheet metals in the seventies of the last century.

A standard method for determining FLD, applied in this paper as well, implies measuring strains on specimens formed by stretching. Strains are measured on the fracture point (upper line on FLD) and localization point (bottom line on FLD). Specimens have different widths, in order to provide more extensive area of positive and negative values of strain φ_2. Figure 8 and Figure 10.a) show forming limit diagrams for steel and Al-alloy, for single-phase and two-phase forming.

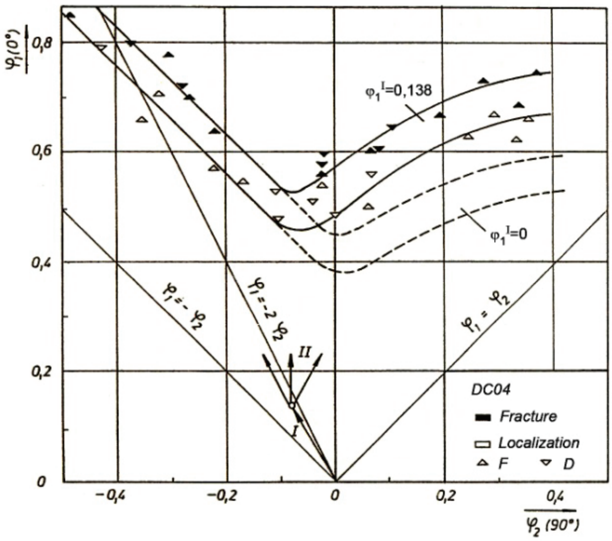

Figure 8: Forming Limit Diagram for steel

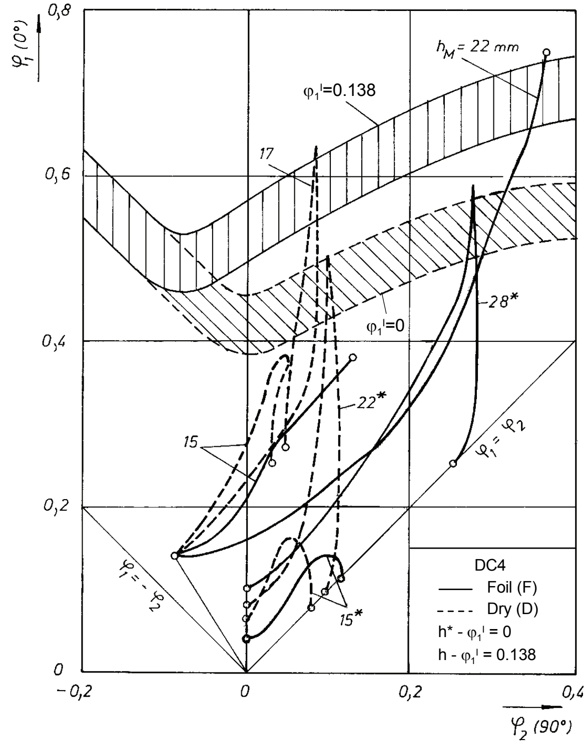

Figure 9: Strain distribution in FLD for steel and two paths /7/

In two-phase drawing of steel sheet metals, the values of realized limit strains are higher than in single-phase, monotonous procedure, but the depths are considerably smaller, fig. When foil is used in two-phase forming (φ_1^I = 0,138), strain φ_1 = 0,78 and depth h = 22 mm are realized; in single-phase φ_1 = 0,6 and depth is 28 mm. In condition D differences are somewhat smaller. In two-phase forming and full lubrication, fracture point moves to the centre of the work-piece, which is consistent with the distribution in hydraulic forming (friction coefficient equals 0), Figure 6 and Figure 7. Such high strain ratio is not accompanied by corresponding stretching depth, which is a sort of contradiction which would not be possible in single-phase forming. Also, the influence of lubrication on realized strain fields is exceptional.

For Al-sheet metals the situation is the opposite. Considering smaller strain ratio in the first phase (φ_1^I = 0,05), the differences in relation to single-phase forming are smaller, as well as sensitivity to contact conditions. With higher strain ratio in the first phase, fracture in the investigation occurred very quickly.

If strain value couples for each measuring point in the main work piece section are inserted in FLD, specific presentations are obtained, which describe the significance of the second principal strain very well, Figure 9 and Figure 10.b). Comparative presentations for steel and Al in Figure 10.b) also describe the ability of the material to avoid localized strain. Generally speaking, in the stretching process, the second principal strain must follow the increase of the first one in order to achieve higher strain ratios. Fracture occurs when the second principal strain no longer increases and that moment is consistent with the localization line. In hydraulic forming, without friction, such a diagram represents a straight line described with $\varphi_1 = \varphi_2$.

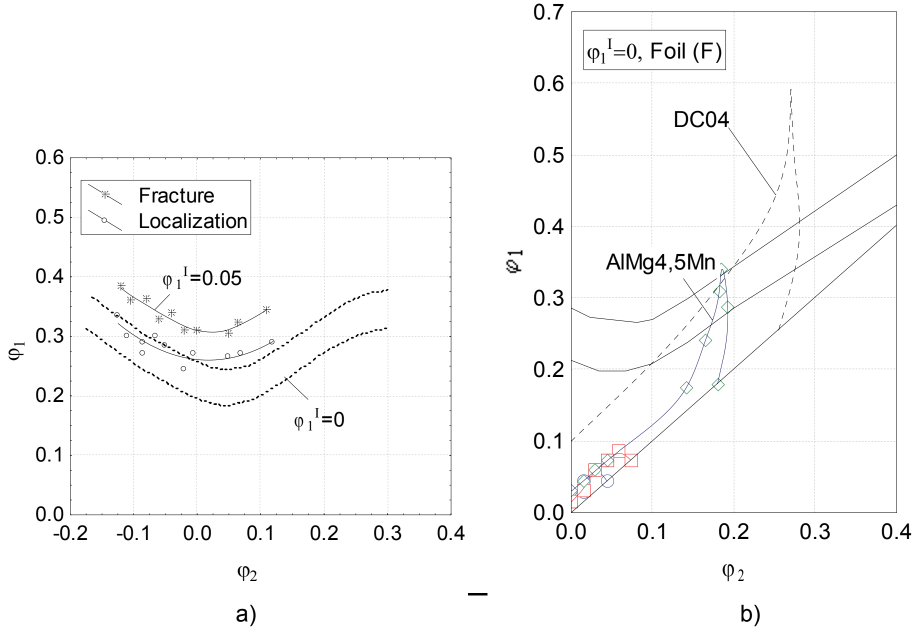

Figure 10: a) Forming Limit Diagram for Al and two paths, b) Strain distribution in FLD for Al and steel

4. CONCLUSION

Biaxial tension – stretching of thin sheet metals is a specific test for defining special formability parameters, but it is also a complex procedure for estimation of tribological conditions in contact of sheet metal and tool. Thereat, general conditions on similarity of stress-strain and tribo-conditions of this model and real deep drawing process must be complied with.

A standard indicator of investigations is the highest realized depth in investigation, forming forces ratio. In conditions of reduced friction, fracture depth, force and the largest realized principle natural strain increase. However, the paper has shown that in conditions of complex strain path, a contradiction occurs – it is possible to achieve higher limit strain ratio, at smaller critical depths. This applies to steel sheet metals and higher amount of realized strain in the first phase in uniaxial tension. In such forming conditions, contact conditions are of extreme importance.

For the reliable analysis of deep drawing, i.e. presented special case of biaxial tension of sheet metals, the necessity of performance of full strain analysis with application of FLD, in addition to the classic approach to the estimation of the influence of working process parameters, has been shown in the paper.

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