Journal for Technology of Plasticity, Vol. 30 (2005), Number 1-2

PREDICTION OF MATERIAL NECKING IN DIGITAL ENVIRONMENT

Tomaž Pepelnjak, Aleš Petek
University of Ljubljana, Slovenia

ABSTRACT

Modern production which is based on metal forming tends to the increased analysis of forming processes in digital environment before the actual production set-up. For all these activities, the quality input data of used material is necessary. Simulations of sheet metal forming demand the input data of friction between the analysed objects, flow curve, yield point, material's anisotropy as well as the level and the course of a forming limit curve.
Some aspects of predicting the forming limit diagrams in digital environment are discussed in this paper in order to omit expensive and time consuming experimental work. Improved method of numerical determination of FLD's in digital environment based on the spatial and time determination of material necking is presented. Influential parameters of Marciniak testing procedure such as the coefficient of friction, mesh size and sampling rate of data acquisition in digital environment have been analysed as well.

Keywords: forming limit diagram, material necking, finite element method, digital environment

1 INTRODUCTION

In modern industrial manufacturing, there are ever more reasons that necessitate the manufacture of technologically very complex components. Due to expensive energy sources and raw materials, various manufacturing procedures are sought that would enable the manufacture of increasingly complex components at the lowest possible energy consumption and minimum material waste. On the other hand, the demand to reduce fuel consumption of transport vehicles forces manufacturers to search for optimum weight to rigidity ratios of installed components. All of these demands encourage manufacturers to search for new materials (e.g. aluminium, magnesium, multiphase and micro-alloyed steels, composite materials etc.), concepts and technologies [1, 2, 3]. These endeavours have resulted in modern manufacturing technologies and concepts, such as tailor weldedblanks (TWB's), tailor rolled blanks (TRB's), 3D profiled blanks, sandwich steel, hydroforming etc. [4, 5]. New technologies and concepts are also implemented in close cooperation with designers and mechanical engineers which leads to ever better optimisation of the manufacturing technology and product costs [6, 7].

In the automotive industry there is also a tendency to shorten assembly times by simplifying assembly operations. This is largely achieved by reducing the number of components which as a result need to have increasingly complex geometrical shapes [2]. Hydroforming procedures have been developed specifically for the manufacture of geometrically most demanding parts which cannot be accomplished using other forming processes. On the other hand, the forming of tailored-made sheet metal parts and tubes with linear or non-linear welds is nowadays common praxis where the workpiece properties have to be fitted according to the demands of forming process and/or part strength, rigidity etc.

In hi-tech processes such as hydroforming or technologically demanding deep drawing of dual and multiphase steels, the process limits have to be well defined. To assure a reliable production, the evaluations in digital environment have to be performed on multi-level product verification.

Nowadays the wide use of hydroforming has been introduced into the production of automotive space frame components, engine cradles, body and safety parts such as windshield headers, pillars, seat frames etc. where tube hydroforming is used. Several components of body in white are in small and medium series production formed with sheet metal hydroforming. This can be performed either in one sheet or double-sheet version [8].

Forming of TWB's is today a common used technology in the automotive industry where the sheet metal blanks have to be adopted in the production process and/or localised part properties (i.e. strength, crash worthiness, rigidity, material cost etc.). Specialised tools are used in most cases when forming TWB's, which can be combined with different sheet thicknesses and/or materials to compensate the differences in sheet thicknesses [9]. Laser welding or mash seam welding are used to perform the linear or non-linear welds of tailored blank. Several materials are used for tailored blanking concept spreading from different steel grades [9] up to aluminium alloys [4, 10]. Unfortunately, the computer programs used for simulations of forming tailored blanks are still based on some simplifications concerning the material properties around the weld line and the weld itself. Despite the specialised modules for analyses of tailored blanking, modern CAE programs for numerical analyses of sheet metal forming, such as PamStamp or Autoform, still assume only those properties of the base material used for tailor blanking. Any hardness changes in the weld or its heat-affected zone are mainly neglected. TRB's are even more difficult to simulate due to thickness transition stretching on a wider area of the blank.

For all above described materials and manufacturing concepts spreading from different steel grades, Al-alloys, Mg-alloys, Ti-alloys up to the processes such as hydroforming and tailor blanking, the forming limit is an important input parameter for digital technology evaluations. One of the most important data when the technological limits for forming of sheet metal and tubular parts are analysed is the so-called forming limit diagram - FLD. Using this diagram, the limits of a material's tearing are taken into account and the forming feasibility can be predicted as well.

2 FORMING LIMIT DIAGRAM

All digital analyses of modern sheet metal forming processes demand well determined forming limits presented in forming limit diagram (FLD) – Fig. 1. There are three possibilities how to determine FLD – analytical, experimental or numerical. The analytical solution, based on theoretical determination of necking and fracture limit is not applicable to a wide range of modern materials.

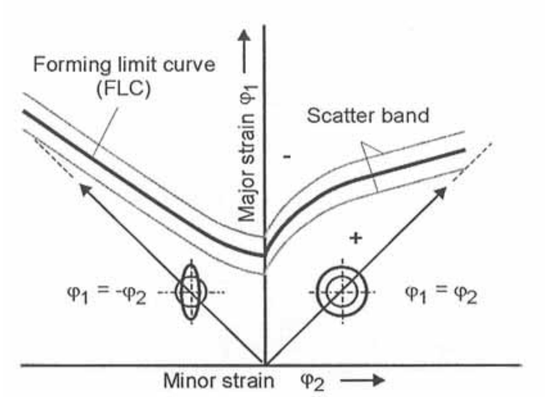
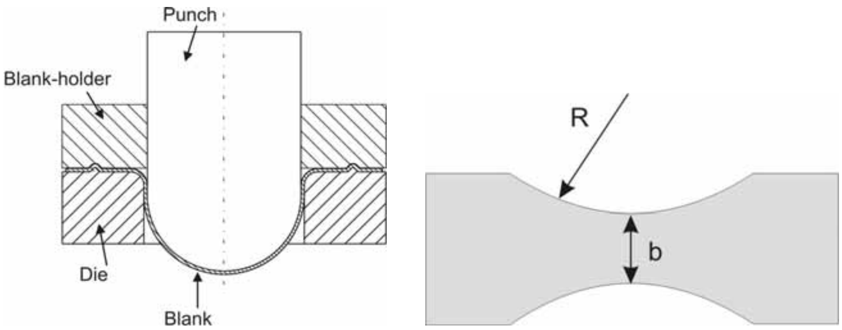
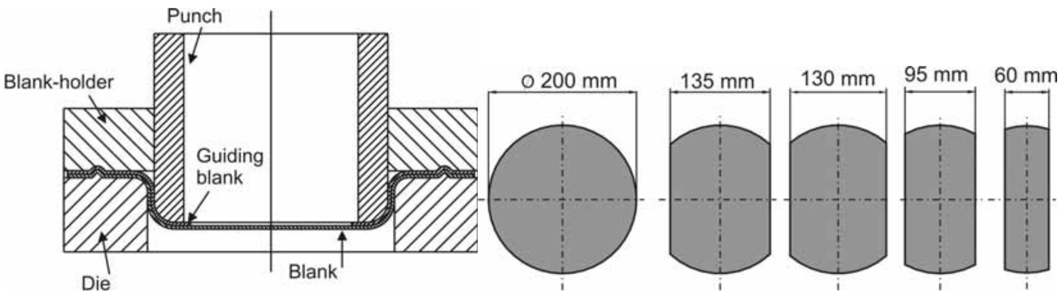


Figure 1: Forming limit diagram [after 11].

Experimental determinations of FLD's are widely used, but unfortunately this concept is time consuming and also affected by the selected testing procedure. Most currently applied testing methods at present are Nakazima and Marciniak. Both methods apply one tooling geometry combined with different test-piece geometries in order to obtain different strain states during the forming process – Fig. 2.



a) Nakazima test



b) Marciniak test

Figure 2: Nakazima and Marciniak test.

The Nakazima test is only slightly affected by the friction coefficient among the tooling and test-part during the testing procedure while the Marciniak is more friction-sensitive. Therefore, some authors favour the Nakazima test. On the other hand the Nakazima method demand**s** optical 3D test-piece evaluation with at least two cameras while the Marciniak test with its plane observed area requires only one camera. Optical evaluation of the material's deformations is nowadays captured by hi-resolution CCD cameras, connected with appropriate computer program to analyse the strain-state of the critical area of the specimen immediately after the performed test. Optical evaluation with circles, squared grid or dots on the surface of analysed sheet metal is used to determine strains during the test.

2.1 Numerical determination of FLD

Experimental determination of FLD's is mostly time consuming and demand**s** expensive test equipment. Therefore, alternative approaches are in progress to determine FLD diagram numerically. They are mainly based on Marciniak-Kuzinsky theory of plastic instability [12] – also known as M-K theory – and different fracture criteria such as ductile fracture criteria analysed by Ozurtuk [13]. When the material thinning is observed, it can be stated that at the material necking localised accelerated thinning occurs. This phenomenon was followed by different authors [14, 15] who determined the FLD's using of numerical approach and finite element simulations. The phenomenon itself cannot be directly connected with M-K theory, but it obviously shows that material starts to neck at the point of accelerated thinning. In 1999 Brun first succeeded to determine necking point and corresponding true strains using the criterion of accelerated thinning. However, using this method the author was not able to determine where the material starts necking.

Therefore, an improved method for FLD determination has been developed in order to determine time and spatial point of material's necking [16]. Based on obtained results of FEM analysis of Marciniak test, the three-step analysis has been performed. Firstly, thickness of all nodes of FEM workpiece has been individually analysed in order to determine minimal thickness for each stored time interval. Secondly, thinning values of all nodes with analysed minimal thicknesses have been stored. Finally, second thinning derivation in time has been analysed – Fig. 3.

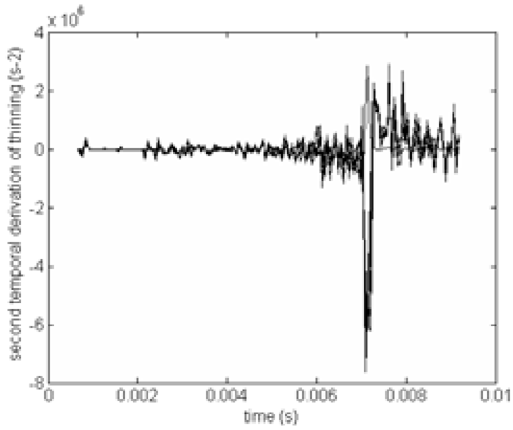


Figure 3: Second temporal derivation of thinning for critical nodes at the specimen with a width of 95 mm.

Among all peaks of analysed nodes, the temporally first one is sought, also following the specialised data purification method and some guidelines for successful data evaluation such as elimination of all peaks following leaping of data due to the effects of numerical simulation [16].

2.2 FEM model

The Marciniak method has been used to simplify the analysis of numerical data due to the plane strain state of the observed area. Different specimen geometries have been analysed in order to obtain an entire range of the analysed FLD. Mechanical properties of the analysed hot galvanised sheet metal are presented in the Table 1. The data are obtained by the uni-axial tensile test.

Table 1: Mechanical properties of the analysed hot galvanised steel.

C = 719.2 MPa	E = 210 GPa
n = 0.153	$\rho = 7850\ kg/m^3$
$r_0 = 0.948$	$\nu = 0.3$
$r_{45} = 0.793$	$s_0 = 0.64$ mm
$r_{90} = 1.003$	

The FEM model (Fig. 4) of all tool parts has been assumed as discrete rigid whereas the guiding plate and the specimen underwent the elasto-plastic potential material law. The Coulomb friction law was assumed for all surfaces in contact using the friction coefficients as follows:

- Die drawbead – blank: $\mu = 0.25$,
- Die radius – blank: $\mu = 0.08$,
- Blank – support plate: different values ($\mu = 0.3$, *$\mu = 0.2$*, $\mu = 0.1$)
- Support plate – blankholder: $\mu = 0.25$,
- Support plate – punch: different values ($\mu = 0.2$, *$\mu = 0.1$*, $\mu = 0.0024$).

Various friction coefficients between the blank and the support plate as well as between the support plate and the punch are not experimentally verified. They aimed only to analyse the influence of the friction coefficient on the course of the Marciniak test. For the mentioned contacts only the friction coefficients presented in italic are obtained with experimental work.

The meshing of all objects necessary for the simulation has been performed mainly with a mapped mesh to eliminate the influence of the mesh shape on the obtained results. Special attention was given to the meshing of the analysed blank, particularly in the central area where the necking and rupture of the test pieces had been expected.

2.3 Influential parameters on numerical FLD determination

The numerical determination of FLD is not dependent on any methodological errors caused by the operator which could however be the case with the experimental one. Unfortunately, FLD can be affected by other different influential parameters. The already mentioned friction coefficients play an important role also when the numerical simulation is performed. Proper selection and determination of friction between the tool and the analysed blank as well as between the blank and the support plate and between the tool and the support plate are of a great importance. Analyses have been performed in two directions to evaluate the influence of the friction coefficient between the above mentioned objects in contact. The evaluated friction coefficients between the support plate and the analysed blank [17] have shown that the higher the friction between both objects is, the better the obtained results are. This also fits to the guidelines of the successful Marciniak test where high friction between the analysed sheet metal and support plate is recommended.

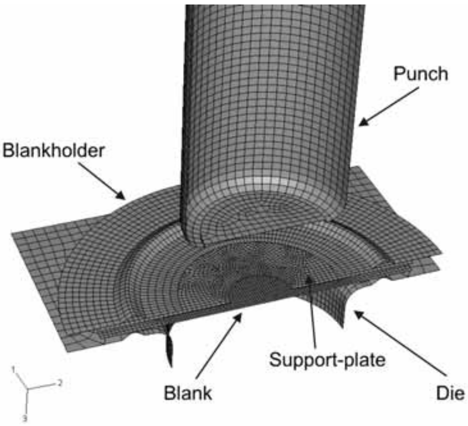


Figure 4: FEM model of the Marciniak test (one half only).

To analyse the influence of the friction among the support plate and the observed specimen, the simulations with three different values of the friction coefficients $\mu = 0.3$, $\mu = 0.2$ and $\mu = 0.1$ have been performed. The influence of the described friction to the strain paths has been analysed on the specimen with a width of 95 mm. The value of the friction has a minor impact on the strain path of the observed node. However, the obtained values of necking points are very similar with all analysed friction coefficients [17].

It is also essential to evaluate the influence of the friction between the punch and the support-plate. As it is known from experimental approach, low friction coefficients between the tool and the support plate with a combination of highest possible friction between the specimen and the support plate are needed. Lubricated contact between the support plate and the punch – deep drawing oil is sufficient – is an assurance that the plate offers the best support to the analysed specimen. Figure 5 shows strain paths for three different friction coefficients between the punch and the support plate: μ=0.2 (dry contact), μ=0.1 (oil) and μ=0.024 (Teflon foil). The influence of described friction coefficient has been analysed on specimens with the width of 60 mm and 95 mm.

To assure that the course of the numerical simulation does not affect the obtained data of the material necking, the simulation with a specimen width of 95 mm has been carried out three times with the same input file. The results of all three simulations have been evaluated with the developed method for necking determination described in Ch. 2.1. The strains of the necking point and the corresponding node numbers for all three simulations are presented in Fig. 6. According to the obtained results it can be concluded that the determination of the necking point is not affected by the course of numerical simulation.

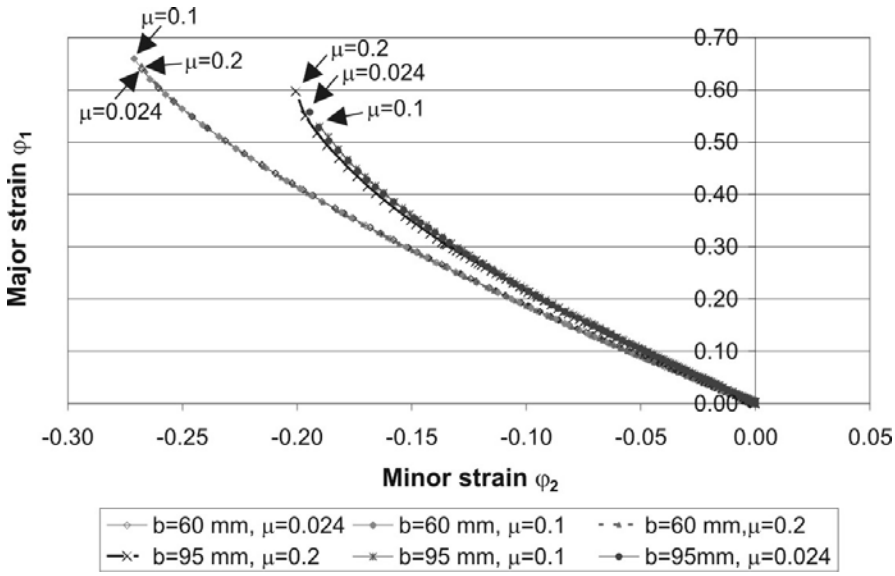
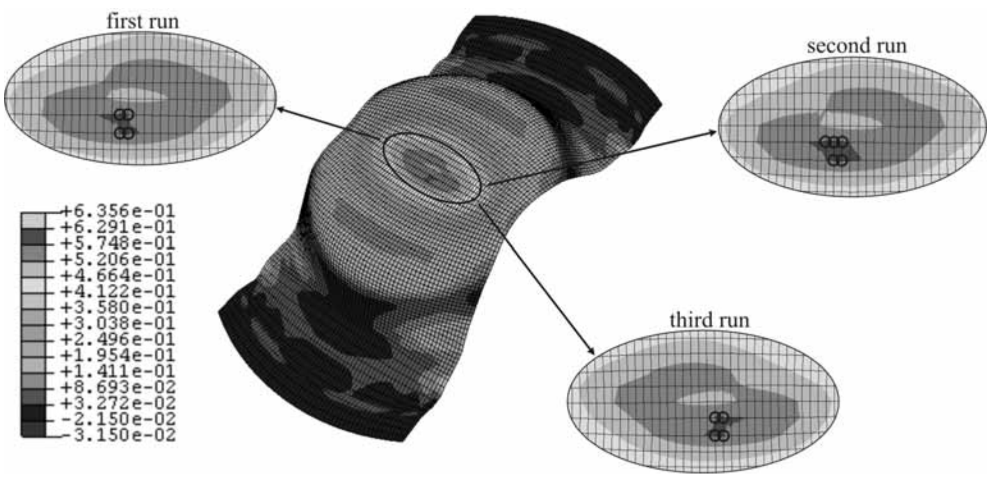


Figure 5: Influence of the friction between punch and support plate on the necking limit.



simulation	φ_1	φ_2
1.	0.513	-0.184
2.	0.514	-0.183
3.	0.512	-0.185

Figure 6: Influence of the course of FEM analysis.

The numerical determination of FLD's is, similar as in the experimental approach, influenced by the sampling rate of the stored data of the observed area of the specimen. Determination of the necking point is based on the stored simulation data whereas too infrequent sampling can lead to inaccurate values of FLD's.
Evaluation of the influence of the sampling rate of the stored data obtained from the used ABAQUS program has been carried out in two steps. Using the explicit simulation code, the selected forming speed was $v_{f,sim}$= 5 m/s. Firstly, during the simulation with a total time of t_{tot}=0.012 s, 200 increments were stored with a sampling rate of t_s=0,06 ms. Based on this sampling rate, the necking point was determined with the described analysis of thinning acceleration. Secondly, another simulation has been performed with a five times higher sampling rate of stored data of t_s=0,0012ms. The influence of the sampling rate on the determined necking point for two strain paths is shown in Fig. 7.

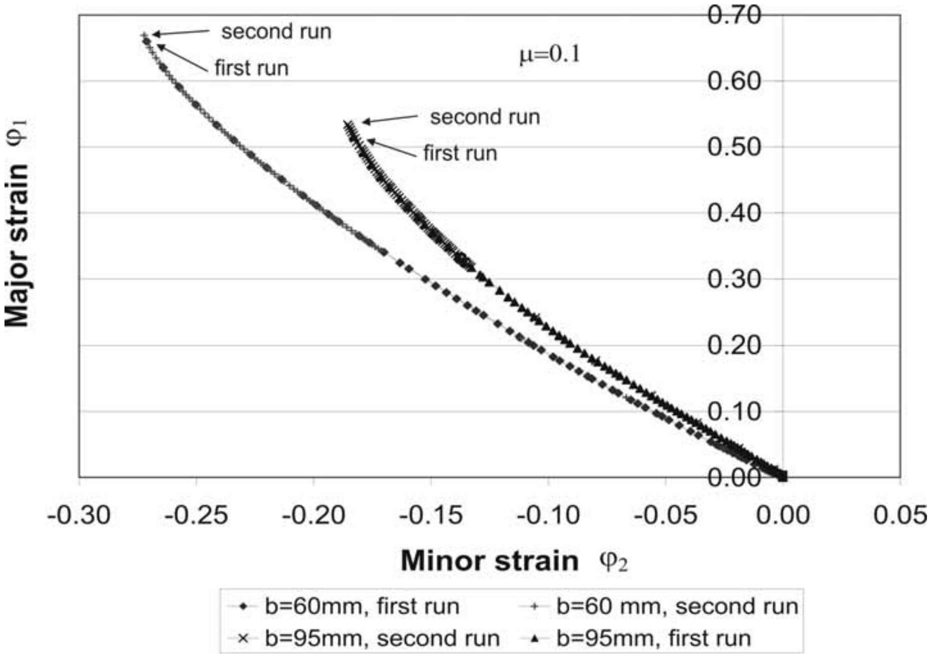


Figure 7: Influence of the sampling rate on the necking limit.

It is evident that the frequency of the stored data has a larger impact on the stored data than the friction between the punch and the guiding plate. If the moment of necking is missed only for one stored time, the error of evaluated strain at first run can be up to 6.5% and only 1.5% at the second run. As observed on the sample with its width of b=95 mm, the necking limit of the first and second simulation differs by 5%. The reason is that the automated procedure calculated two different necking nodes on the same analysed specimen. However in most comparisons being performed between the first and the second evaluation of material necking, this phenomenon occurred on the same node.

3 OUTLOOK

The presented method of digital determination of FLD's has been until now analysed on steel with C=720 N/mm^2 and n value of 0.15. Modern materials such as stainless steels, high strength steels, multi-phase steels, aluminium alloys and magnesium alloys etc. have to be analysed in the continuation of the presented work. The materials with high *r* values are of great interest as well. The sensitivity of the developed method on accurate necking determination shall be also verified on those materials with *n* values below 0.1. However, the first research work in this area is already in progress.

As already known, the material thickness has also an influence on the values of the forming limits of the analysed material. Therefore, the analyses of a wider range of different thicknesses varying from 0.25 mm up to some millimetres are to be performed. Here it is necessary to evaluate the sensitivity of the presented method for automated determination of the necking point on sheet thickness.

However at the beginning of the paper, modern concepts such as hydroforming, TWB's and TRB's were presented as well. The most difficult task when these materials are analysed is to determine their material properties in a digital environment. With the quality inputs of those properties the presented method for the automated evaluation of the necking should be reliable to determine the material limits for those processes as well.

4 CONCLUSIONS

Modern materials and concepts developed to decrease the mass of the part with a simultaneous increase of its strength, rigidity and crashworthiness, need a quality determination of forming limits. These are best described in forming limit diagrams. They are mostly obtained with experiments which are consequently being a rather expensive and time consuming approach. In this respect determinations of FLD's based on a numerical approach are an interesting alternative.

The parameters influencing such a determination of FLD's have been analysed. The importance of a particular parameter has shown that the friction coefficient between the punch and the support plate has some influence on the level of the determined necking point. The strain path is not affected due to this observed parameter. The friction coefficient between the support plate and the analysed specimen has a slightly higher impact. The friction between these two sheet metal parts has a minor influence on the value of the determined necking limit whereas the strain paths are influenced through these friction values.

To neglect the influence of the course of the numerical analyses, the same FEM problem has been processed three times. Data evaluation has shown identical times for necking the limit and minimal deviations in corresponding strain values.

The most important observed parameter has been the sampling rate of the stored numerical data obtained from the ABAQUS simulation. A too infrequent sampling rate may have an impact on the proper determination of the necking limit. Therefore, in the proximity of the necking time the sampling rate has to be as high as possible.

In the future research work, different modern materials have to be analysed in order to prove the reliability of the necking determination. The presented method based on the second thinning derivation in time combined with data purification shall also be further automated to shorten the evaluation times.

5 REFERENCES

[1] De Cooman B.C.: Structure–properties relationship in TRIP steels containing carbide-free bainite, Current Opinion in Solid State and Materials Science, Volume 8, Issues 3-4 , June-August 2004, p. 285-303

[2] D. Schmoeckel et al.: Metal forming of tubes and sheets with liquid and other flexible media, Annals of CIRP, Vol 48/2/1999

[3] Z. Kampuš, J. Jiang, B. Dodd: Net Shape Cold Plastic Forming of Aluminium-Based Metal Matrix Composites. J. mater. sci. lett., 1994, let. 13, str. 80-81.

[4] F. Vollertsen, M. Kreimeyer, M. Beckmann: Deep drawing of laser welded aluminium-steel/aluminium-titanium tailored blanks, Proc. of IDDRG 2003 Conference, 11-14.maj 2003, Bled, str. 273-282.

[5] T.W. Ku, B.S. Kang, H.J. Park: Tailored blank design and prediction of weld line movement using the backward tracing scheme of finite element method, Int. Journal of Advanced Manufacturing Technology, 25 (1-2): 17-25, JAN 2005

[6] G. Gantar, M. Ljevar, K. Kuzman: Uporaba numeričnih simuliranj pri razvoju orodij za izdelavo pločevinastih sestavnih delov avtomobilov = The use of numerical simulations in the development of tools for the sheet-metal parts of cars. Stroj. vestn., 2001, Vol. 47, št. 10, p. 605-614.

[7] K. Kuzman: Prispevek k hitremu razvoju in izdelavi orodij za globoki vlek pločevine = Contribution to the fast sheet metal deep drawing tool development and production. Stroj. vestn., 1999, Vol. 45,nr. 6, p. 238-249.

[8] P. Hein and F. Vollertsen: Hydroforming of sheet metal pairs, Journal of Materials Processing Technology, Vol. 87 (1999), 1-3, p. 154-164

[9] T. Pepelnjak, K. Kuzman: Feasibility study of forming of tailored blanks in conventional tools, Laser Assisted Net Shape Engineering 3: Proceedings of the 3rd LANE 2001, Erlangen, August 28.-31., 2001. Bamberg: Meisenbach, 2001, p. 483-494.

[10] M. Merklein, M. Geiger: New materials and production technologies for innovative lightweight constructions, Journal of material processing technology, Vol. 125: Sp. Iss. SI SEP 9 2002, str. 532-536

[11] M. Geiger, M. Merklein: Determination of Forming Limit Diagrams – A New Analysis Method for Characterization of Materials' Formability; Annals of the CIRP Vol. 52/1/2003.

[12] Z. Marciniak, K. Kuczinski, T. Pokora: Influence of the Plastic Properties of the Material on the Forming Limit Diagram for Sheet Metal Tension, Int. J. Mech. Sci., 15 (1973), p. 789-805.

[13] F. Ozturuk, D. Lee: Analysis of forming limits using ductile fracture criteria, J. Mat. Proc. Technol., 147 (2004) p. 397-404.

[14] R. Brun, A. Chambard, M. Lai and P. de Luca: Actual and virtual testing techniques for a numerical definition of materials; Proc. NUMISHEET'99; Besançon, France, 1999, p. 393-398.

[15] T. Pepelnjak, A. Petek, K. Kuzman: Analysis of the Forming Limit Diagram in Digital Environment, Sheet Metal 2005, Erlangen 5.-8. April 2005, Germany, p. 697-704.

[16] A. Petek, T. Pepelnjak, K. Kuzman: New method for determination of FLD in digital environment, Journal of Mechanical Engineering, Vol. 51 (2005), 6, p. 330-345.

[17] T. Pepelnjak, A. Petek, K. Kuzman: Determination of forming limit diagrams in CAE environment, Proc. of 5th ICIT conference, Velenje, 12.-15.4.2005, p. 361-366.

ODREĐIVANJE LOKALIZACIJE DEFORMACIJE U DIGITALNOM OKRUŽENJU

Tomaž Pepelnjak, Aleš Petek

REZIME

Moderna proizvodnja koja je bazirana na tehnologiji plastičnog deformisanja u sve većoj meri se oslanja na analizama procesa u digitalnom okruženju, pre konkretne primene. Za takvu vrstu analiza od izuzetne je važnosti kvalitet ulaznih podataka vezanih za materijal. Na primer, kod simulacije obrada lima neophodni su ulazni podaci o trenju, krivi tečenja, anizotropiji materijala kao i okrivi granične deformabilnosti i istorije deformisanja.
U ovom radu prikazani su neki aspekti određivanja dijagrama granične obradivosti u digitalnom okruženju. Na taj nacin se izbegavaju skupi i kompleksni eksperimenti. Dat je prikaz poboljšane metode numerickog određivanja krive granične deformabilnosti. Analizirani su uticajni parametri u Marciniak experimentu od kojih su najznačajniji: koeficijent trenja, veličina mreže, način akvizicije podataka i dr.
Mehanicke osobine materijala koji je korišćen u istraživanju su:

$C = 719.2$ MPa
$E = 210$ GPa
$n = 0.153$
$r = 7850$ kg/m3
$r_0 = 0.948$
$n = 0.3$
$r_{45} = 0.793$
$s_0 = 0.64$ mm
$r_{90} = 1.003$

U daljem radu na ovoj problematici predviđa se uključivanje većeg broja različitih materijala u istraživanju.