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THE SYSTEM FOR SHEET FORMING DESIGN

SYSTEM DIAGNOZOWANIA PROCESÓW TŁOCZENIA BLACH

In the paper the modern sheet metal forming process design technique and diagnostic system is described. The system incorporates the forming limit stress diagrams and the wrinkling stress diagrams as the limit conditions of forming into the commercial finite element method programme MARC. The constitutive equations and boundary conditions, good describing the materials reaction on the complex deformation conditions are also included. To build such system for the sheet metal forming design the following partial tasks had to be solved: development of the theoretical calculation of forming limit stress diagram by using different yield criterion and its experimental verification, elaboration of wrinkling stress criterion and its experimental verification, elaboration of the model describing boundary conditions between sheet metal and tools in plastic deformation processes, development of constitutive equations more precisely describe behaviour of used sheet metals, creation of mathematical model of selected deep drawing processes for laboratory and industrial applications.

The forming limit stress diagrams was created on the base of theoretical calculation and experimental research. The original and modificated M-K theories and perturbation analysis in theoretical calculation of the forming limit stress diagram were used. The choice of yield criterion has a great effect on the predicted strain and stress limit. As a basic yield criterion the Hill's new anisotropy function was used.

The wrinkling criterion was build on the base of shell theory. The sheet metal buckling during forming operation was considered as the bifurcation type buckling of the shell in elastic-plastic range. On the base of FEM analysis the critical condition of wrinkling onset for each element at successive time increment are found. The material models and friction conditions were established in the forms of equations on the base of the experimental researches. The forming analysis was performed with MARC K7.2 finite element software package using rigid-plasgic flow method. The tooling shape for analysis was converted from Pro/Engineer system into IGES formats and meshed pre-processing MENTAT 3.2 program.

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Application of the system for sheet metal forming design (SSMFD) creates the possibility to design the sheet metal forming processes without expensive and time consuming trail and error techniques so that the necessity of investigation of metal forming processes by using of the rea tools may be reduced or eliminated. The system will able to predict the forming loads, to create the geometry of the deformed sheet and tools, to distribute the strain and stress and to determine the process conditions. The SSMFD uses the final shape and size of formed parts, material properties, rate of deformation (punch velocity) and boundary condition as input parameters, and a discretized mesh to represent the sheet blank dimensions. Application of the SSMFD in industry will make the production of sheet parts more competitive and cheaper.

W pracy przedstawiono nowoczesny system do projektowania i diagnozowania procesów kształtowania plastycznego blach. W opracowanym systemie połączono wykresy naprężeń granicznych dla procesów kształtowania blach i wykresy naprężeń fałdowania z profesjonalnym programem MARC wykorzystującym metodę elementów skończonych. Do programu MARC wprowadzono równania konstytutywne i warunki brzegowe poprawnie opisujące reakcję materiału na złożone warunki odkształcania. Dla zbudowania takiego systemu konieczne było zrealizowanie następujących zadań cząstkowych: rozwinięcie teoretycznej metody wyznaczania wykresów naprężeń granicznych dla blach z zastosowaniem różnych warunków plastyczności i jej eksperymentalna weryfikacja, opracowanie kryterium fałdowania blach i jego doświadczalna weryfikacja, opracowanie modeli opisujących warunki tarcia w procesach przeróbki plastycznej, zastosowanie równań konstytutywnych dokładnie opisujących zachowanie się badanych blach, zbudowanie opisu matematycznego wybranych procesów tłoczenia blach przydatnego do badań laboratoryjnych i zastosowań przemysłowych.

Wykresy naprężeń granicznych opracowane zostały na podstawie analizy teoretycznej i badań doświadczalnych przy zastosowaniu oryginalnej i zmodyfikowanej teorii M-K oraz analizy perturbacyjnej. Wybór warunku plastyczności wpływa istotnie na naprężenia i odkształcenia graniczne. Jako podstawowy warunek plastyczności przyjęto anizotropowy warunek Hilla.

Kryterium fałdowania zbudowano w oparciu o teorię powłok. Fałdowanie blachy w operacjach tłoczenia było określane z teorii bifurkacji powłok w zakresie sprężysto-plastycznym. Stosując MES określano krytyczne warunki fałdowania w poszczególnych elementach dla kolejnych przyrostów czasu. Modele materiału i tarcia przedstawiono w postaci równań opracowanych na podstawie badań doświadczalnych. Do matematycznego modelowania wybranych procesów kształtowania blach zastosowano metodę sztywno-plastyczną. Kształt narzędzi z programu PRO/Engineer transformowano do formatu IGES i preprocesora MENTAT 3.2.

Zastosowanie opracowanego systemu do projektowania procesów kształtowania blach umożliwia projektowanie procesów tłoczenia jedynie przy użyciu technik komputerowych bez konieczności stosowania drogiej i czasochłonnej metody prób i błędów. System umożliwia określenie siły tłoczenia, geometrii tłocznych półfabrykatów i narzędzi, określenie rozkładu odkształceń i naprężeń i warunki procesu. Danymi wejściowymi są końcowe rozmiary i kształt wyrobu, właściwości materiału, prędkość odkształcania i warunki brzegowe. Rozmiary materiału wyjściowego określano poprzez jego dyskretyzacje. Zastosowanie opracowanego systemu w przemyśle powinno obniżyć koszty produkcji i zwiększyć konkurencyjność wyrobów.

1. Introduction

Sheet metal forming operations are standards manufacturing processes, which enable to obtain different types of drawpieses. The complexity of these processes leads to numerous techniques to predict or evaluate the formability of the raw materials. In the last years, important developments have been achieved, based on the theoretical analysis, experimental investigation and industrial practice. An extensive effort has been devoted to provide the design engineer with analytical tools for design at the computer terminal so that the expensive trail and error process with the real tools may be reduced or eliminated.

Formability is a complex engineering concept, which cannot be defined by a single measure. Instead it must be broken down into a number of components. Formability analysis of sheet materials is usually evaluated through the concept of forming limit diagrams (FLDs). [1, 2]. The construction of an FLDs for particular materials is basically experimental but some analytical models were also developed [3—6].

The FLD is difficult to use for sheet metal forming process design becasue it is strongly dependent on the strain path. It means that for nearly local area of deformed materials in the case of complex drawpieces, the different FLDs should be applied. Considering this fact the forming limit stress diagram (FLSD) instead of FLD was proposed [7, 8]. The only one FLSD can be used for calculation of different FLDs at various strain paths. In the numerical simulation of deep drawing operations by using finite element method (FEM) the FLSD could be applied directly as a stop test.

Only in the last years with the advance in computer usage and FEM codes the theoretical study of 3D sheet metal forming operations has become possible. If FEM simulation is involved in iteration procedure of process design the process may be changed according to the obtained simulation results and changes can be incorporated in the tool shape. The absence of FLSD or FLD modules in the finite element programmes makes unable to determine the onset and propagation of localised necking. The finite element simulation besides the FLSD or FLD should incorporate the wrinkling limit diagram (WLD) module. Modificated by this way finite element programmes should be include already in the planning phase in order to optimise the products and processes. So a drastic reduction in the time and cost of initial adaptation of the tools and easy determination of the process parameters with a simultaneous improvement in the product quality and process reliability will be achieved. The correct choice of numerous interactive variables: material behaviour, boundary conditions, forming equipment, strain rate etc has appeared as one of the main aims of the modern industry.

2. Objectives and methods of researches

The aim of the work is to develop the modern sheet metal forming processes design technique and diagnostic system. The proposed method incorporates into the FEM programme the FLSDs and the WSDs modules, as the limit conditions of forming. In the programme constitutive equations (CE) and boundary conditions (BC), good describing the materials reaction on the complex deformation conditions are included. The material models and friction conditions were established by a proper set of the experiments. The elaborated system using commercial finite element package MARC becomes available to realistic analysis, simulation and designing of sheet metal forming processes. That way engineers involved in process design will receive a voluable tool, in the form of computer procedure. The algorithm of the system is shown in Fig. 1.

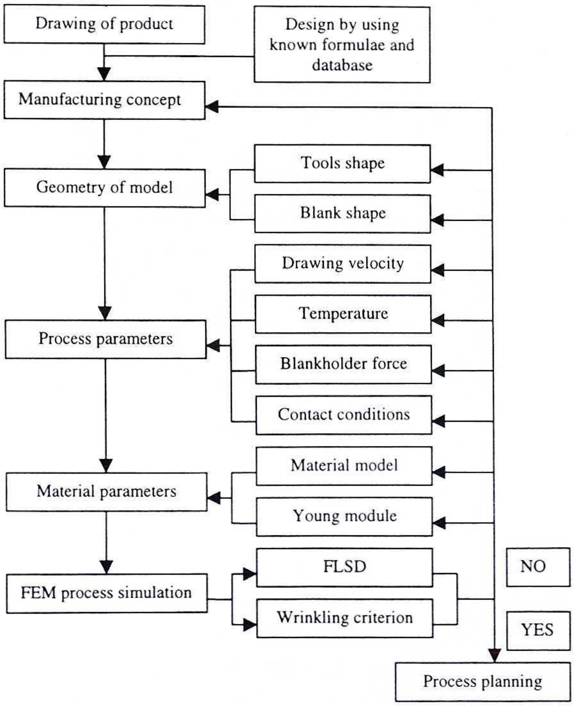


Fig. 1. The algorithm of the system for sheet metal forming design

The work contains the following tasks:

- development of the theoretical calculation of forming limit stress diagram by using different yield criterion,
- experimental verification of the elaborated forming limit stress diagrams,
- elaboration of wrinkling stress diagram and its experimental verification,
- elaboration of the model describing boundary conditions between sheet metal and tools in plastic deformation processes,
- development of constitutive equations more precisely describe the behaviour of used sheet metals,
- creation of mathematical model of selected deep drawing processes on the base of MARC package for laboratory and industrial application.

3. Elaborating of FLSD

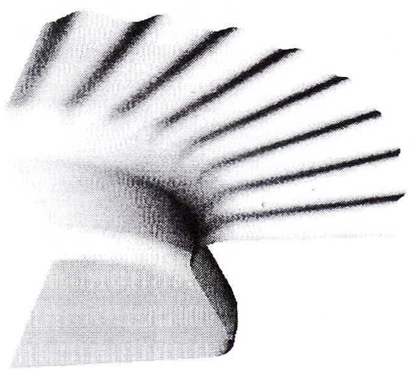
The FLSD was created on the base of theoretical calculation and experimental research [9, 10]. Original and modificated M-K theories [3] and perturbation analysis [11] in theoretical calculation of the FLSD were used. The choice of yield criterion has a great effect on the predicted strain and stress limit [12]. As a basic yield criterion the Hill's new anisotropy function was used [13]. In the calculation of FLSD the following assumption were invoked: the sheet metals have anisotropy properties, strain path has significant influence on the formability of materials, sheet metals is strain hardening and strain rate sensitive. The anisotropy parameters were determined in the standard tensile tests. Calculation of exponent m in Hill's yield function was conducted by comparison of the stress-strain curves from buckling test and uniaxial tensile test [14]. In the FEM simulation the FLSD was used to predict the strain instability as well as to determine directly the stress limit in deformed drawpieces.

4. Elaboration of wrinkling stress diagram

Wrinkling of the sheet metal during forming takes place in the area of the sheet where compressive stress in sheet plane is excessive. For deep drawing process two types of wrinkling may occur (Fig. 2). First one is wrinkling of a flat blank (Fig. 2a) and the second one is wrinkling of unsupported walls (Fig. 2b). The reason and character of both of them is the same it means the excessive compressive stress.

The flat blank wrinkling is relatively easy to predict and suppress by blankholder force. This force is usually small in comparison to drawing force and its effect on restrain of drawing process is relatively slight. The unsupported wall wrinkling (Fig. 2b) is difficult to predict and prevent during sheet forming operations. The preventing of the wrinkling can be obtained by change of stress state in the wall only

a)



b)

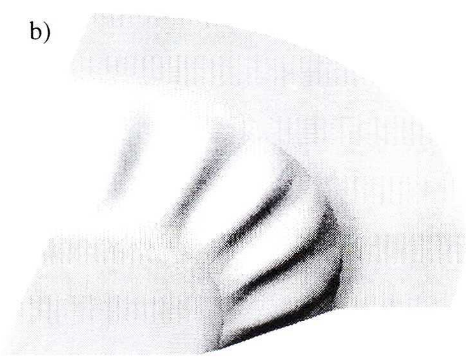


Fig. 2. The wrinkling of: a) — a flat blank and b) — a wall unsupported by tools

in such the way that critical conditions for wrinkling will not be gained. The change of stress state can be controlled by blankholder force, drawbead force and by change of blank shape. For sheet metal forming process designers the knowledge about critical conditions of wrinkling and relation between stress state in critical area and process parameters are very important.

In the conventional point of view the experimental study of wrinkling and application of the experimental data to the process design can solve the problem. This method assures reliable data but only for conditions comparable with experimental ones. The other method is elaboration of wrinkling criterion on the base of theory of plasticity. After experimental verification, such criterion should be more universal and could be used in a wide range of material properties and forming conditions.

The wrinkling criterion was build on the base of shell theory because deformed thin sheet metals satisfies the shell conditions. The shell space is separated from Euclidean space by outer and inner surface and by boundary of the shell. The geometric and kinematics relations, yield condition and constitutive equation were written for middle surface. The set of equations together with boundary conditions allow to obtain solution for analysed shell. The equations in elastic and plastic range were incorporated to FEM programme together with shell type elements. On the base of FEM analysis the critical condition of wrinkling onset for each element at successive time increment are found. The systems for sheet metal process analysis using universal FEM packages usually have included neither wrinkling criterion nor post buckling modelling in plastic straining.

One of the most important problems associated with theory and analysis of shells is stability problem. The K o i f e r works [15] brought in remarkable contribution in that subject mainly for elastic structures, but even in that range of deformation the important difficulties remain due to the great number of freedom degrees and the very rapid increase of computational time with structural complexity increase. These difficulties are naturally increased if some parts of the structure enter the plastic domain.

The sheet metal buckling during forming operation was considered as the bifurcation type buckling of the shell in elastic-plastic range. The indispensable simplification for wrinkling analysis was made on the base of shell theory and condition of drawing processes.

Equation for critical stress is derived with assumption of double curved shell and coincidence of coordinate system with principal directions. The proper choice of wrinkling direction is important for avoiding of calculation indeterminacy. For flat surface, where curvatures are equal to zero critical stress can not be determined.

As a result the following relation for critical wrinkling stress was obtained

$$\sigma_1^{cr} = \frac{1}{\sqrt{3}} \frac{h}{R_2} \left(L_{11} L_{22} - L_{12}^2 \right)^{1/2}, \tag{1}$$

where: h — local thickness, R_2 — main curvature radius, L_{ij} — stiffness module.

Critical wrinkling stress depends directly on the geometry of shell and on module L_{ij}. The modules are function of effective strain and stress. Geometry as well as stress and strain states at onset of wrinkling are taken from FEM simulation data.

All the data needed for calculation of critical stress (1) are accessible by FEM analysis of deep drawing process.

These data are:

- geometric data — local thickness h and local radius of curvature R_i,
- local effective strain,
- local effective stress
- principal stresses.

For each increment during FEM modelling of the sheet metal forming processes the wall areas unsupported by tools are defined. The instantaneous stiffness module L_{ij} and critical stress are calculated. The last step is the comparison of the critical stress to the adequate local stress. If the local stress is greater or equal to the critical stress then the wrinkling can occur.

5. Determination of constitutive equations of used sheet metals

Constitutive equations describing flow stress σ_p as a function of forming conditions form a bridge through which the knowledge on the behaviour of materials can be used in the broadly understood engineering design of processes, new materials and manufacturing. The works towards the development of better material models have been conducted in the last years at different scientific centres [16—19].

Sheet metal forming processes usually are performed at ambient temperature, and very rarely at higher temperatures. The structural softening processes do not take place in materials deformed at room temperatures, so the effect of deformation history can be neglected. In that situation it can be assumed that mathematical models describing the strain hardening curves depend on the strain ε and strain rate $\dot{\varepsilon}$ only. For these assumptions the following equations were applied:

$$\sigma_p = C(\varepsilon + \varepsilon_0)^n \tag{2}$$

$$\sigma_p = C(\varepsilon + \varepsilon_0)^n \dot{\varepsilon}^m \tag{3}$$

$$\sigma_p = C(\varepsilon + \varepsilon_0)^{n_1} \exp(n_2 \varepsilon) \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{(a_1 \varepsilon + a_2 \varepsilon^2)} \tag{4}$$

where: C, a_i — material constants, ε_0 — pre-strain, n_i, — coefficient of strain hardening, m. — strain rate sensitivity coefficient.

The best results were obtained for equation (4), but the equation contains fifth coefficients difficult to calculation.

The tensile tests of investigated sheet metals were performed with initial strain rate of $1.2 \cdot 10^{-3} s^{-1}$ by using the standard tensile specimens at three directions of 0,45 and 90 degree to rolling direction. The normal plastic anisotropy was evaluated by using the chemical grid printed on the sample surface. The results obtained by using equation (2) for aluminium A1, steel Soldur 340 and titanium sheets are given in Table.

TABLE

Parameters in work hardening equations of investigated materials

Material	Angle to rolling direction, deg	E MPa	Coefficients			Normal anisotorpy
			C, MPa	n	ε_0	
Aluminiu mA1	0	58000	131.2	0.239	0.006	0.93
	45	58000	144.0	0.288	0.010	0.52
	90	58000	127.0	0.236	0.006	1.23
Steel SOLDUR 340	0	198000	752.0	0.240	0.027	0.82
	45	200000	773.0	0.270	0.042	0.77
	90	201000	779	0.250	0.031	0.81
Titanium	0	950000	718.7	0.190	0.001	1.70
	45	105000	588.9	0.158	0.014	2.00
	90	985000	600.0	0.124	0.025	2.20

6. The boundary conditions

Friction is one of the most important factors that determines the plastic deformation in sheet metal forming operations and therefore is very importance in reliable finite element simulations of these processes. Any attempt to simulate the sheet metal forming processes without a detailed consideration of the friction effect on the process is incorrect. The frictional behaviour of the sheet metal depends on several parameters like: contact pressure, sliding velocity, sheet- and tool material, surface roughness, lubricant and plastic deformation. Especially when the blank thickness/blank area ratio is small the friction greatly influences the material flow and the final strain distribution. Because nearly all of these factors vary with the local position, it is necessary to use the friction model based as close as it is possible on local contact conditions.

The main questions in the tool/sheet metal contact frictional behaviour may be formulated as follow:

— what kind of test should be used for determining the frictional characteristic in sheet metal forming processes?

— what factors play significant role in friction of sheet metal forming processes?
— is the Coulomb friction model capable to describe the real friction coefficient in sheet metal forming processes?
— what is appropriate model of friction phenomena in sheet metal forming processes?

Different fiction testing devices have been developed for sheet metal forming simulation [20—25]. On the base of theoretical study and analysis of the friction phenomena in sheet metal forming processes the new universal friction test device was developed. The friction test device contains sixteen fixed or rotated cylindrical beads located in four rows. The device gives a four or more types of strip sample testing configuration [26]. The device can be used to calculate the friction coefficient and to simulate the sliding with concurrent thickness reduction or bending and unbending under tension type strip drawing tests. Moreover the restraining force for arbitrary drawbead geometry can be determined. The last one is very important in order to develop an equivalent drawbead model in FEM simulations.

The simplest configuration of the beads used in friction coefficient test calculation is shown in Figure 3.

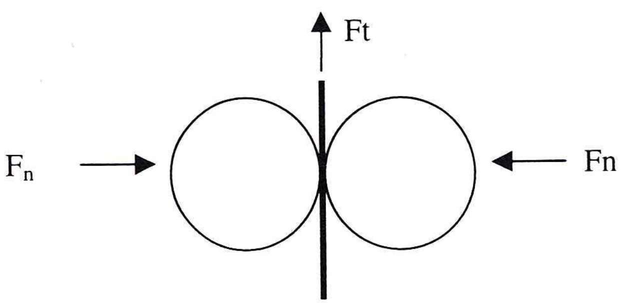


Fig. 3. The scheme of test for friction coefficient determination

The sheet strip was drew with the force F_t between two beads clamped together with the force F_n. During the test the strip was elongated to the different degree. The friction coefficient μ was calculated by using following formula

$$\mu = \frac{F_t - 2F_n[\Delta t/(4R - \Delta t)]^{0.5}}{2F_n + F_t[\Delta t/4R - 4t)]^{0.5}} \tag{5}$$

where: F_t, F_n are pulling and clamping force respectively, measured during sheet strip drawing between two cylindrical dies, R is the radius of the die arc and $\Delta t = t_0 - t$ represents strip thickness reduction during the test.

Using two level fractional factorial designs, the different variables have been studied for steel, titanium and aluminium sheets. In summary of experimental analysis it can be stated that the most influencing factors are: rolling direction, sliding velocity, plastic strain, tool radius and lubricant. The effect of plastic strain and tool radius can be replaced by one parameter only that is contact pressure.

The investigated factors produce significant dispersion effect on Coulomb friction coefficient. For example for steel sheet, the friction coefficients vary between 0.132 and 0.230. It means, that constant friction model is no satisfactory for accurate simulation. In order to achieve better results of computer simulations, value of friction coefficient should be adjusted to the local conditions.

The friction models for wider range of tribological conditions have been predicted for investigated sheet metals. For steel sheet, the model is expressed as follows:

$$\mu = 0.206 - 7.971v - 0.017s + 8.96 \cdot 10^{-5}p, \tag{6}$$

where: v — sliding velocity [m/s], p — contact pressure [MPa], s — lubricant conditions: 1 for dry friction, 2 when lubricant is used. Close to 90% of friction coefficient variability is explained by the above model. Comparing above mentioned factors in different areas of formed part one can predict the friction coefficient variability and decide if constant or various values of friction coefficient is acceptable in FEM.

In finite element modelling of drawbeads a large number of elements have to be used therefore long computation time is required. For this reason the different equivalent drawbead models were elaborated [27, 28]. The model take into account restraining force caused by complex deformation, change of sheet thickens and material work hardening. It is therefore very important for practical appliation to evaluate drawbead effect on the processes as a function of its geometry. Variation of the restraining force can be obtained by varying the beads radius and contact angle.

Conducted experiments shown that friction is very complex phenomenon and depends on many factors, so it is difficult to create universal mathematical model that could be used for friction force description. It was assumed that future users of the system for sheet metal forming design should determine the friction coefficients using elaborated testing device and mentioned above most influencing factors.

7. Creation of mathematical models of deep drawing processes

It has been demonstrated that FEM analysis can be readily applied to simulate actual sheet metal forming processes. The forming analysis was performed with MARC K7.2 finite element software package using rigid-plastic flow method. The rigid-plastic method was chosen because this method reduces the total computation time in comparison with the explicit method. The tooling shape for analysis was converted from Pro/Engineer system into IGES format and meshed pre-processing MENTAT 3.2 program. The details of performed FEM analysis (used FEM method, organisation of MARC system, creating models: geometry of parts, material properties, boundary conditions and contact options) was presented in the [9, 10]. The mathematical model of selected deep drawing processes was elaborated for steel, titanium and aluminium [29, 30]. In the computer simulation the constitutive equations (4) Young's modulus, Poisson's ratio and the friction coefficient of the tested sheets (6) were used. For the rigid-plastic option nodal based friction was used in calculation. This is because it improves the solution accuratness. Five layers were used through the thickness of the shell finite elements. All tools were modelled as rigid and coefficient of friction was associated with each tool. One-quarter of the analysing geometry was used due to symmetry for easier visualisation and for reducing the quantity of the finite elements. The contact tolerance distance was 0.02 mm. The rigid surfaces are offset from the blank by half of thickness of the blank, because the contact algorithm takes into account the shell thickness. For initial strain below yield stress the stress-strain relation has elastic form and is described by Young modulus.

All the selected processes were analysed for different conditions it means: different punch velocities, initial shapes of blank, blankholder forces and friction conditions. The theoretical results were determined for observe experimental strain level at necking and all other conditions were in agreement with experiment. The calculated results were compared with experimental strain level at necking and the experimental punch travel. The numerical tools to be really useful, must be able to predict the onset of the plastic instability, and so they contain a criterion for the prediction of the onset of localised necking and wrinkling.

The system was applied for the axisymetrical cylinder, conical and hemispherical cups and more complex shapes as rectangular and *L* shape parts of different dimensions. The results of simulation were shown for *L* shape box.

7.1. Simulation of the *L*-shape box deep drawing process

The FEM simulations were performed on the full 3D model for SOLDUR 340 steel. The initial blank geometry was rectangular shape of 255 mm by 200 mm. A maximum of 300 increments was carried out in rigid-plastic flow method. During the analysis the punch moves with velocity of 3 mm/s. The results of the simulations of deep drawing *L*-shape box for steel are presented on the following figures 4—6 for punch travel equal to 18 mm. The figures show the distribution of the thickness, equivalent stress and equivalent plastic strain and in Fig. 6 the principal stress and strain components with respect to the FLSD and FLD are shown additionally. Experimental and theoretical failure region was placed in area of the radius roundness of the drawpiece. The present results are in good agreement with experimental date.

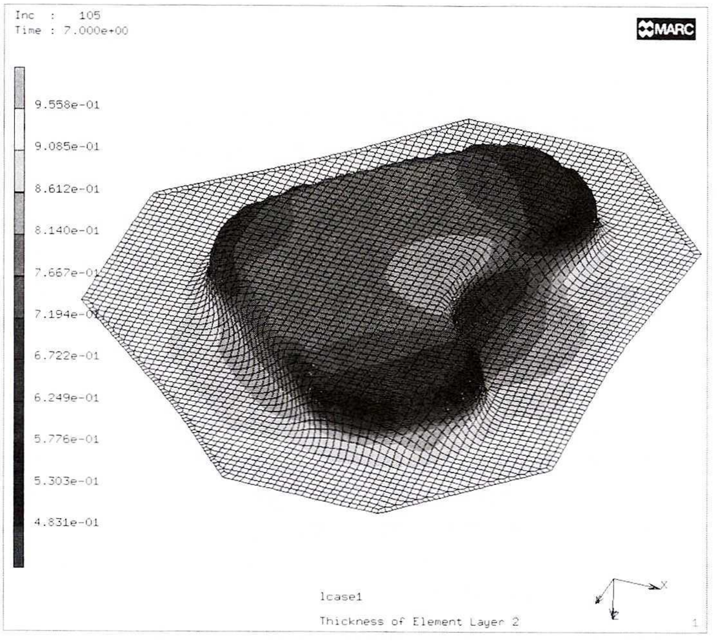


Fig. 4. Distribution of thickness in L-shape box at punch travel to 18 mm

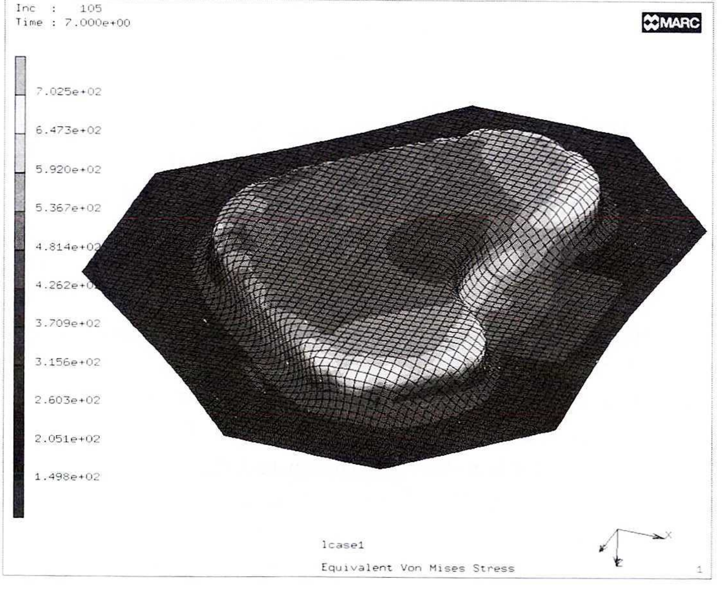


Fig. 5. Distribution of effective stress in L-shape box at punch travel to 18 mm

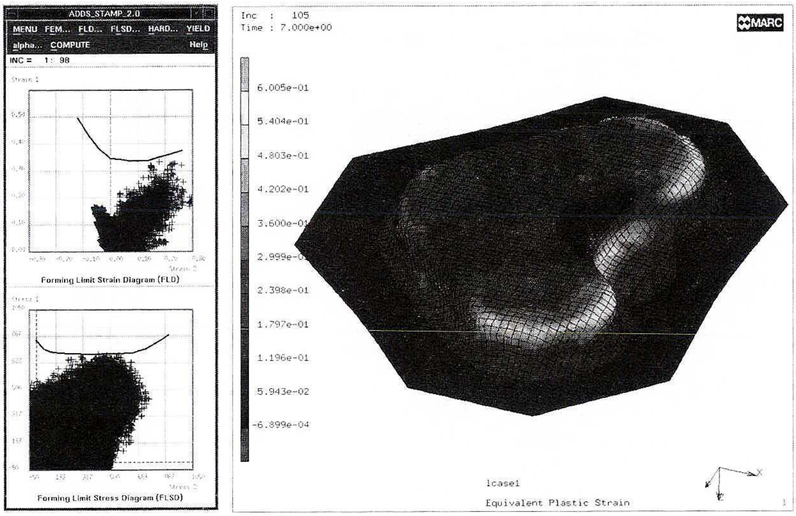


Fig. 6. Distribution of effective strain in L-shape box at punch travel to 18 mm and principal stress and strain components with respect to the FLSD and FLD

8. Conclusion

Application of the system for sheet metal forming design (SSMFD) creates the possibility to design the sheet metal forming processes without expensive and time consuming trail and error techniques so that the necessity of investigation by using of the real tools may be reduced or eliminated. The system is able to predict the forming loads, to create the geometry of the deformed sheet and tools, to distribute the strain and stress and to determine the process conditions. The SSMFD uses the final shape and size of formed parts, material properties (FLSD, WSD and CE), rate of deformation (punch velocity) and boundary condition as input parameters, and a discretized mesh to represent the sheet blank dimensions. Application of the SSMFD in industry will make the production of sheet parts more competitive and cheaper.

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